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Case Study Open Access

Study on the Application of Full-process Mechanization in Green and Efficient Production of High-quality Rice: A Case Study of Mashan Agricultural Service Center in Shangyu District

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Abstract This study explored the application of full-process mechanization in the green and efficient production of high-quality rice by taking Mashan Agricultural Service Center in Shangyu District, Zhejiang Province, as a practical case. Against the background of rapid agricultural modernization and increasing demand for green agricultural development in China, the study examined how regional agricultural service centers integrate mechanized seedling cultivation, machine transplanting, field management, plant protection, harvesting, drying, storage, and rice processing into a coordinated agricultural production system. Based on field materials, project documents, and operational cases, the study analyzed the service model, equipment configuration, production organization, and operational effects of the Mashan center. The results showed that full-process mechanization significantly improved rice production efficiency, reduced labor dependence, lowered grain losses during harvesting and postharvest stages, and enhanced the stability and quality consistency of high-quality rice production. In particular, centralized seedling cultivation, emergency mechanized harvesting during typhoon periods, and expanded grain drying capacity played important roles in strengthening regional food security and disaster-response capacity. The study also found that agricultural service centers can effectively bridge the gap between small-scale farmers and modern agricultural technology through socialized agricultural services. At the same time, several challenges remain, including high machinery investment costs, shortages of skilled technicians, uneven mechanization levels among farmers, and increasing climate-related risks. Therefore, future development should focus on improving regional agricultural service networks, strengthening agricultural talent training, promoting practical intelligent agricultural machinery, enhancing digital management, and extending the high-quality rice industry chain. The findings of this study provide practical references for promoting sustainable rice production and agricultural modernization in major rice-producing regions of China.

Keywords Full-process mechanization; High-quality rice; Agricultural service center; Green agricultural production; Rice mechanization

1 Introduction

Rice is not only a staple crop in China, but also a strategic crop closely tied to national food security, rural livelihoods, and regional agricultural modernization. A recent review of Chinese rice production showed that total rice output rose steadily from 2001 to 2021, and that the rise was driven largely by improvements in yield per unit area rather than by expansion of planted land. That long-term trend is encouraging, but it also means that future gains must come less from acreage growth and more from better organization, better varieties, and better management, especially in ecologically and economically advanced provinces where land and labor are both costly. Tang et al. (2022) further noted that rice production in China increasingly depends on coordinated improvements in varieties, field management, and agricultural resource use, rather than on one single input alone.

Yet the everyday reality of rice farming is still shaped by production bottlenecks. Recent studies on rice production efficiency in China indicate that mechanization and custom machine services already have measurable influences on technical efficiency, although the effects remain uneven across production stages and farm scales. The problem is not simply whether machinery exists, but whether farmers can access appropriate machinery and integrated services at critical farming periods. Supporting services such as seedling cultivation, pest management, drying, storage, and transportation must be organized into a coordinated production chain. This issue is particularly important for small-scale farmers, who often cannot afford independent machinery investment but still require professionalized and standardized services to avoid yield and quality losses (Cai et al., 2024; Zeng et al., 2025).

The greening of rice production adds another layer to this challenge. Green agricultural production does not imply reducing mechanization; instead, it requires more precise and scientifically managed mechanized operations. Studies conducted in southern China demonstrated that agricultural socialized services can improve fertilizer-use efficiency and enhance technical performance among small rice farmers by lowering information barriers and increasing access to specialized agricultural knowledge. Other studies also showed that mechanization contributes not only to labor saving and output growth, but also to improvements in green grain productivity when combined with low-carbon production practices and trans-regional machinery coordination (Ma et al., 2023; Shi et al., 2023; Cai et al., 2024).

Zhejiang Province provides a particularly valuable context for this discussion. In 2024, Zhejiang Province issued policy guidelines encouraging the accelerated construction of modern agricultural service centers, aiming to establish a professionally managed agricultural service network by 2027. The policy emphasized full-process mechanized farming, centralized seedling cultivation, grain drying, digital agriculture, emergency agricultural response systems, and brand-oriented agricultural development as key directions for future modernization. At the local level, Shangyu District has been recognized for four consecutive years as a major grain-producing county in Zhejiang Province. According to the 2024 regional statistical communiqué, the district maintained approximately 483,200 mu of grain-sown area, while local government documents also identified Shangyu as a pilot area for rice machine-transplanting subsidy programs. These policy and production conditions make Shangyu an important case for understanding how regional agricultural service centers translate provincial modernization strategies into practical agricultural operations.

This study therefore focuses on one central question: how does a regional agricultural service center transform full-process mechanization into a practical model for the green and efficient production of high-quality rice? To answer this question, the study takes Mashan Agricultural Service Center as a representative case. The center is not treated as a universally perfect model, but rather as a practical operational example that helps translate abstract agricultural modernization policies into observable field practices. The study links recent research on agricultural mechanization and socialized agricultural services with a traceable local case involving seedling cultivation, mechanized field management, emergency harvesting, grain drying, processing, and rice brand development.

2 Overview of the Study Area and Agricultural Service Center

2.1 Basic situation of rice production in Shangyu District

Shangyu District is located in Shaoxing, in the economically dynamic and agriculturally intensive part of eastern Zhejiang. In such areas, rice production operates at the intersection of two strong forces. On one side, there is pressure from urbanization, labor transfer, and competition for land and labor. On the other, there is strong policy support for grain security, high-standard farmland, higher yields, better quality, and greener production methods. The district's 2024 development statistics reported 483,200 mu of grain-sown area and highlighted Shangyu's role as a grain-producing county, its machine-transplanting subsidy pilot work, and the establishment of large high-yield rice demonstration blocks. These facts suggest that Shangyu is not a marginal rice area, but a place where rice remains an important component of local agriculture and where policy attention to rice production is unusually strong.

Rice production in eastern China is also increasingly quality-oriented. Nationally, rice output growth has depended heavily on yield enhancement, but local consumers and public procurement systems now care not only about quantity, but also about eating quality, uniformity, safety, and market identity. Zhejiang's 2024 provincial notice on leading crop varieties and promoted technologies, together with its long-running "Zhejiang Good Rice" selection program, reflects this shift from basic output protection to quality-centered, greener, and more branded rice development. In such a policy environment, high-quality rice production is best understood not as a niche activity, but as a mainstream direction for local grain agriculture.

The local rice landscape around Mashan combines relatively open paddy fields with infrastructure suited to mechanized operations. Level rice fields, irrigation ditches, road access along the field edge, testing plots for quality varieties, and nearby drying and service facilities. Full-process mechanization depends on field conditions, access roads, service dispatch capacity, and post-harvest facilities just as much as it depends on the machines themselves. In regions where fields are physically operable and service centers are close enough to dispatch machinery rapidly, the organizational value of mechanization increases sharply. This point is broadly consistent with studies showing that land conditions, service access, and operation scale jointly affect machinery utilization and production efficiency in Chinese rice systems (Wang et al., 2023).

2.2 Construction of mashan agricultural service center

Mashan Agricultural Service Center is located in Mashan Village, Shangyu District, and was built and is operated by the Shaoxing Shangyu Mashan Grain Specialized Cooperative. The project covers 6.73 mu and includes a drying center of 2,400 square meters, a seedling cultivation center of 1,888 square meters, and a machinery shed of 200 square meters. Total investment exceeded RMB 6 million. The center was designed with relatively clear functional zoning, including repair rooms, machine sheds, processing rooms, storage rooms, drying rooms, and training or meeting spaces. The same materials state that the center has seven fixed workers, around 100 sets of agricultural machinery and equipment, machine assets valued at roughly RMB 8 million, and a 100% licensing rate among machinery operators.

This basic profile matters for two reasons. First, it shows that the center is not a symbolic public building; it is a working service platform built around operational capacity. Second, it demonstrates a familiar but important principle in agricultural modernization: service centers succeed when they combine physical infrastructure, machinery, people, and organizational routines, rather than treating mechanization as a matter of equipment ownership alone. Zhejiang’s 2024 policy on modern agricultural service centers explicitly stressed the need for coordinated functions such as full-process mechanized operation, centralized seedling cultivation, drying and processing, technical services, and training, and the Mashan center closely matches that policy logic in built form (Figure 1).

Figure 1 Aerial view of Mashan Agricultural Service Center and surrounding paddy landscape (Photoed by Xinfeng Ren)

The aerial image of the center reinforces this interpretation. The service buildings are embedded directly within a rice-producing landscape, with easy road access and visible proximity to operational fields. This spatial arrangement is part of the center’s practical value. A center that sits close to its service area can move seedlings, machines, and harvested grain quickly, which is essential during narrow operation windows and emergency weather periods. That operational closeness is also consistent with Zhejiang’s larger goal of building a five-kilometer agricultural service circle so that support is delivered near the field instead of from distant, fragmented providers.

2.3 Main facilities and equipment configuration of the service center

Mashan’s internal logic is structured around the most time-sensitive links in rice production: seedling cultivation, field operations, emergency harvesting, drying, storage, and simple processing. The center’s original facilities included drying rooms, processing rooms, machine sheds, storage spaces, and a dedicated seedling center. A later expansion added 805 square meters of built area, eight more dryers, a 750-ton indoor metal granary, a 50-ton rice processing line, and additional service spaces needed for centralized seedling cultivation and machinery support.

This expansion raised the center’s single-batch drying capacity to 400 tons and increased annual drying capacity from 10,000 tons to 18,000 tons. In practice, such post-harvest investment is one of the clearest signs that the center is operating as a full-chain rice service platform rather than as a simple machine dispatch unit. For high-quality rice, harvest is not the last decisive step. Drying conditions strongly affect the physical, processing, and nutritional quality of grain. Recent drying studies show that drying temperature, humidity, airflow, and moisture conditions influence cracking risk, whole-rice rate, germination quality, and postharvest stability, while scientific drying design can reduce losses and support quality retention (Li et al., 2024).

The center’s equipment structure also reflects a service philosophy centered on coordination. Machinery and facilities are not isolated investments, but linked assets: centralized seedling equipment supports machine transplanting; harvest machinery feeds directly into drying; drying supports storage and processing; processing supports branding and marketing. This chain approach aligns with broader findings that agricultural mechanization becomes more productive when it is embedded in service systems rather than treated as a stand-alone farm input (Liu and Li, 2023; Ruan et al., 2025).

2.4 Service scope and service model for high-quality rice production

Mashan’s service model as a “1+8” system built around full-process mechanized services and supported by drying and processing, centralized seedling cultivation, agricultural technical services, input delivery, machinery maintenance, agricultural study and training, product marketing, and storage and preservation. Four specialized teams have already been formed for mechanized operations, input delivery, technical services, and machinery repair.

They distinguish between a core neighboring service area and a broader regional service reach. The center provides “nanny-style” services for around 5,000 mu of nearby farmland and can deliver more than 50,000 mu-times of full-process mechanized services each year. The center provides integrated agricultural services to a 55,000-mu rice-and-wheat production area across seven surrounding towns and streets. Read together, these figures suggest a layered service pattern: intensive nearby support, combined with wider regional outreach through cross-village operation teams. Such a layered service structure is consistent with recent literature showing that service-scale operation and land-scale operation are complementary rather than mutually exclusive in promoting machinery utilization and reducing per-unit machinery costs (Zeng et al., 2025).

The service model is also important for how it deals with smallholder constraints. Smallholders do not necessarily need to own the entire set of modern inputs and machines. What they need is dependable access to those inputs and operations at the right time, with predictable service quality and reasonable cost. The best recent work on agricultural socialized services in China argues that these services matter most where they reduce timing constraints, improve technology accessibility, and bridge the organizational gap between small-scale farming and modern agricultural systems. Mashan’s “service center + specialized teams + nearby and regional operations” model fits that logic closely (Cai et al., 2024; Zeng et al., 2025).

3 Application of Full-process Mechanization in Green and Efficient Production of High-quality Rice

The key value of full-process mechanization lies in coordination across production stages. A rice production system becomes truly “full-process” only when the earlier stages are designed to support the later ones, and when grain quality is protected from seedling cultivation to post-harvest handling (Table 1). In the Mashan case, the service center does not function as a loose collection of separate services, but as an integrated chain in which field timing, machine scheduling, seedling quality, drying capacity, and technical guidance support one another.

Table 1 Full-process mechanization chain in high-quality rice production

Link	Main practice at Mashan	Main contribution
Centralized seedling cultivation	Unified nursery preparation and tray seedling supply	More uniform seedlings and lower household labor demand
Mechanized transplanting	Timely transplanting through service teams	Reduced labor bottlenecks and more standardized planting
Mechanized field management	Organized water, fertilizer, and technical guidance	Easier adoption of standardized management
Green plant protection	Scaled plant protection and technical support	Lower missed-control risk and more targeted pest management
Combine harvesting	Rapid harvester dispatch during peak season	Better timeliness and lower field losses
Grain drying and processing	Centralized drying, storage, and rice processing	Lower postharvest loss and better quality retention

This framework is consistent with recent studies on rice mechanization, which increasingly emphasize that labor saving alone is not enough. Seedling supply, service accessibility, harvest timing, drying control, and postharvest organization are all important in determining whether mechanization can improve rice production in a stable and environmentally reasonable way (Liu and Li, 2023; Li et al., 2024; Ruan et al., 2025).

3.1 Mechanized application of centralized rice seedling cultivation

Centralized seedling cultivation is the first key threshold in many machine-transplanted rice systems. If seedlings are weak, uneven, or not available on time, later mechanized operations lose part of their value. Recent research on machinery rice transplanting and centralized rice seedling cultivation in China shows that modern seedling centers do more than save labor. They improve seedling supply efficiency, raise the use efficiency of nursery space, and make large-scale machine transplanting easier to organize (Ruan et al., 2025).

The Mashan materials show this logic clearly. The center includes a dedicated seedling cultivation area and provides more than 200,000 trays of early- and late-rice seedlings annually for local farmers. The project materials also report that technical guidance associated with the center helped improve seedling establishment rates for surrounding farmers by about 20%. Although these figures are operational records rather than controlled experimental data, they still show a practical point: standardized seedlings are one of the most direct ways to improve later field performance.

This stage also has a green-production meaning. Centralized seedling cultivation can reduce repeated household-level preparation, lower waste in nursery materials, and make seed treatment and early-stage management easier to standardize. More importantly, it creates the basic condition for timely transplanting. Delayed or uneven transplanting often leads to uneven tillering, uneven maturity, and later problems in water control, pest prevention, and harvesting. By contrast, centralized seedling supply supports more synchronized crop growth, which is especially valuable in quality-oriented rice production.

3.2 Mechanized rice transplanting and field management

Mechanized transplanting is one of the most visible signs of modern rice production in eastern China, but it should be understood as a service system rather than only a machine operation. Shangyu’s local policy documents in 2024 clearly aimed to improve the local machine-transplanting rate through targeted subsidy support, indicating that machine transplanting is not only a farm-level choice but also a district-level policy priority.

In the Mashan case, machine transplanting is embedded in organized service delivery. The center’s mechanized operation teams provide field services across nearby and broader regional rice areas, reducing the need for farmers to coordinate seedling transport, machine booking, and field labor by themselves. The practical gain is not only labor substitution, but also the reduction of uncertainty and delay. Research on rice production efficiency in China has shown that mechanization affects production efficiency differently across cultivation stages, and that its benefits are stronger when service access and operation timing are reliable (Shi et al., 2021).

Field management in a full-process system also becomes easier once transplanting is standardized. Uniform transplanting density and timing allow more consistent irrigation, fertilizer scheduling, and pest monitoring. In this sense, mechanized transplanting works as an organizational bridge between pre-production and in-season management. The Mashan materials further indicate that the center organizes technical training and expert guidance, especially during periods of high pest pressure. This suggests that field management is treated not as a purely mechanical issue, but as a combined agronomic and service task.

3.3 Green pest control and mechanized plant protection

Green pest control is sometimes misunderstood as the opposite of mechanized plant protection. In practice, the two can support each other when operations are timely, targeted, and professionally managed. Rice fields are highly sensitive to missed control windows, especially under humid and high-risk conditions. Small farmers working alone may delay control because of labor shortage, equipment limitations, or uncertainty about when and how to act. Agricultural socialized services can reduce these bottlenecks by making both technical advice and field operations more accessible (Shi et al., 2023).

The Mashan materials report that the center regularly organizes technical exchanges and invites district-level machinery and agronomy experts to provide field guidance during periods of frequent pest occurrence. More than 20 training sessions had been organized, and pest diagnosis and control had covered more than 5,000 mu. These details suggest a service model in which green plant protection is not limited to pesticide application, but includes diagnosis, timing, technical instruction, and operation support.

Recent research on UAV-based herbicide application in direct-seeded rice found that UAV systems could achieve weed control effects comparable to conventional knapsack systems under suitable conditions, while reducing labor burden and operator exposure (Paul et al., 2024). This finding should not be applied mechanically to every rice production context, but it supports a broader principle: plant protection can become greener when application is more precise and professionally managed.

For a service center like Mashan, the green value of mechanized plant protection lies mainly in timeliness, standardization, and risk reduction. Timely intervention helps avoid later over-application caused by delayed action. Standardized service can reduce variation caused by different farmers using different equipment and habits. Professionalized service also lowers the barrier to adopting improved control methods. In this sense, “green” means better organized and more accurate input use, not simply less machine use.

3.4 Application of mechanized rice harvesting

Harvest is the stage where yield, labor, weather, and grain quality meet most directly. Rice can tolerate some management imperfections during the growing season, but harvest delays under rain, typhoon conditions, or limited machine access can quickly lead to lodging, high-moisture grain, shattering, quality decline, and grain loss. This is why harvest is a central test of whether full-process mechanization works in practice.

The literature is clear on this point. A review of rice harvest losses shows that losses occur not only during reaping, but throughout the harvest process, including threshing, winnowing, transportation, and storage transfer. Poor harvest management, inappropriate techniques, and weak infrastructure all contribute to those losses (Qu et al., 2021).

For Mashan, mechanized harvesting is one of the center’s most visible strengths. The internal materials report that during the overlap of the “double rush” farming season and typhoon weather, the center deployed more than 20 harvester operations for emergency early-rice harvesting, completed urgent harvesting on more than 12,000 mu, and dried more than 14,000 tons of grain afterward (Figure 2). These figures do not represent a controlled experiment, but they clearly demonstrate operational capacity during a period when timeliness matters most.

Figure 2 Combine harvesting in the rice fields served by Mashan Agricultural Service Center (Photoed by Xinfeng Ren)

The field photograph of combine harvesters operating in the paddy landscape makes the service-center logic visible. In good weather, mechanized harvesting improves labor efficiency. In bad weather, it becomes a risk-management tool. A center able to quickly mobilize harvesting capacity across several towns is not only improving efficiency, but also performing a quasi-public service by protecting grain from weather shocks. Zhejiang's 2024 policy on modern agricultural service centers also encouraged centers to build emergency response teams and integrate them into local agricultural disaster-response systems, and Mashan's emergency harvesting case fits that policy direction closely.

3.5 Mechanized grain drying and processing

For high-quality rice, harvest without drying is incomplete mechanization. Grain that is harvested on time but not dried promptly may still suffer quality and safety losses. Drying affects grain cracking, storage stability, whole-rice rate, appearance, and later processing performance. Recent studies on rice drying have shown that carefully controlled drying conditions can improve both drying efficiency and grain quality, while poor drying management can quickly weaken the advantages of timely harvesting (Li et al., 2024).

The Mashan case gives drying a central place in the production chain. According to the internal project materials, the center added eight dryers after expansion and raised batch drying capacity to 400 tons, while annual drying capacity increased from 10,000 tons to 18,000 tons. The center also expanded grain storage through a 750-ton indoor metal granary and built a 50-ton rice processing line (Figure 3). These facilities make it possible to move from field rescue to stable postharvest management, and then from postharvest management to value-added rice products.

This stage is especially important in regions with narrow harvest windows and unstable autumn weather. Centralized drying reduces dependence on household sun drying, which is weather-sensitive, land-intensive, and difficult to standardize. It also supports grain safety, reduces the risk of mildew and quality deterioration, and creates the condition for processing and branding. In quality-oriented rice systems, this is a major bridge between agricultural production and the consumer market. Mechanized drying is therefore not simply a postharvest convenience. It is an essential part of green and efficient production because it prevents avoidable loss of grain already produced with limited land, water, energy, and labor resources (Qu et al., 2021; Li et al., 2024).

4 Promotion Effects of Full-process Mechanization on High-quality Rice Production

4.1 Improvement of rice production efficiency

The most immediate effect of full-process mechanization is improved production efficiency, but the term "efficiency" deserves a broader reading. It certainly includes speed and labor saving. Yet in rice production it also includes the ability to complete operations within the proper agronomic window, to reduce coordination failures, and to maintain service continuity across production stages. Research on Chinese rice production has shown that mechanization and custom machine services are positively associated with production efficiency, while empirical work on grain production capacity more broadly has shown that mechanization can improve both output capacity and production efficiency (Shi et al., 2021; Liu and Li, 2023).

Figure 3 Grain drying line and postharvest facilities at Mashan Agricultural Service Center (Photoed by Xinfeng Ren)

In Mashan’s case, the efficiency effect appears not only in machine deployment, but in service organization. The center provides specialized teams, centralized seedlings, coordinated field operations, rapid harvest dispatch, drying, storage, and simple processing. That integrated structure lowers the number of separate transactions farmers must manage by themselves. It also reduces the risk that one weak link will delay the next. For example, the value of machine transplanting rises when seedling supply is standardized; the value of harvesting rises when drying capacity is immediately available; and the value of production increases when technical guidance accompanies physical operations.

Recent studies from southern China suggest that agricultural socialized services raise technical efficiency among smallholder rice producers and can improve grain yield per unit area through pathways such as greater machinery use, more moderate scale operation, and more grain-oriented planting structure. These mechanisms are particularly relevant to Mashan, which operates through both nearby “nanny-style” services and broader regional service provision (Cai et al., 2024; Liao et al., 2025).

4.2 Enhancement of high-quality rice production quality

High-quality rice production depends on more than high yield. It requires good seedlings, orderly field development, timely harvest, sound drying, and stable postharvest handling. In recent years, rice research has increasingly emphasized this combination of yield, grain quality, process quality, and consumer quality. Tang et al. (2022) linked long-term improvements in Chinese rice production to coordinated advances in varieties and management, while Li et al. (2024) showed that drying conditions shape processing and nutritional outcomes.

Mashan’s mechanized chain supports quality in several ways. Centralized seedling cultivation improves the consistency of field establishment. Mechanized transplanting makes crop growth more uniform. Technical guidance helps farmers respond more quickly to pest pressure. Combine harvesting reduces delays at maturity. Centralized drying reduces the instability of household sun drying and better protects grain at high moisture. Finally, a local processing line makes it easier to turn paddy into a recognizable rice product under local brand management.

The center’s internal materials further report that the registered “Xinfeng” rice brand won the Silver Award in the 2024 “Zhejiang Good Rice” competition. Even though the branding result itself is not a scientific measure, it is meaningful in an applied production study because it suggests that mechanized service capacity is being connected to quality recognition in the marketplace. Zhejiang’s official rice-brand promotion program also shows that the province evaluates rice not just on output, but on physicochemical quality, eating quality, safety indicators, and the traceability of production processes. Viewed in that light, Mashan’s brand result is best understood as the downstream expression of upstream production standardization.

4.3 Reduction of production costs and grain losses

The economic value of mechanization should not be measured only by lower labor input per hectare. In many rice regions, the larger gain comes from replacing uncertain, fragmented, or delayed operations with reliable service. Smallholders often cannot justify separate investment in nurseries, transplanting machinery, dryers, storage, and processing facilities. Service centers lower that barrier by spreading fixed costs across a larger service area. This is one reason agricultural socialized services matter so much in Chinese smallholder systems. They do not eliminate smallholders; they lower the cost of connecting them to modern agriculture (Zeng et al., 2025; Liao et al., 2025).

Loss reduction is equally important. Qu et al. (2021) showed that rice losses accumulate across the harvest process, including reaping, threshing, winnowing, transportation, and storage transfer. In a service-center context, grain loss is reduced not only because machines are faster, but because operations are organized in sequence. Prompt harvesting followed by immediate drying is far more effective than improving either link alone.

Mashan's emergency harvest case illustrates this clearly. The center did not merely send harvesters into the field; it paired harvest rescue with large-scale drying. That combination matters, especially under typhoon conditions, when wet grain can deteriorate rapidly after harvest. The center's expansion from 10,000 tons to 18,000 tons of annual drying capacity also suggests that the operators understood postharvest loss reduction as a core public and economic function, not as a secondary activity. In applied terms, this is one of the strongest arguments for full-process rather than partial mechanization: effective systems reduce both visible labor costs and less visible losses.

4.4 Promotion of green agricultural development and resource utilization efficiency

Green agricultural development is often discussed in broad policy language, but at farm scale it usually depends on a few concrete conditions: reducing unnecessary input use, improving operational precision, lowering waste, avoiding weather-related loss, and organizing production in ways that use land, labor, and machinery more efficiently. In rice systems, agricultural socialized services have been shown to encourage greener behavior among smallholders, while broader work on grain systems in China suggests that mechanization can support improved grain production capacity and resource-use efficiency when it is combined with organized services and coordinated operations (Liu and Li, 2023; Shi et al., 2023).

There is also emerging agronomic evidence that some mechanized rice cultivation systems can align productivity with environmental goals. A recent field study from the Taihu Lake region found that rotary tillage plus mechanical transplanting produced higher and more stable rice productivity while maintaining lower methane emissions and lower yield-scaled global warming potential than plowing plus mechanical transplanting. The exact agronomic conditions of that experiment differ from those at Mashan, but the broader implication is important: mechanization and greener outcomes are not inherently contradictory. The outcome depends on how tillage, planting, timing, and management are combined.

In Mashan, the green effect of full-process mechanization appears through organization. Centralized seedling production avoids repeated household-level preparation. Mechanized transplanting improves timeliness. Technical service encourages more standardized field management. Professionalized plant protection makes it easier to target inputs. Combine harvesting and centralized drying reduce avoidable loss of grain already produced. Storage and processing prevent further postharvest waste and create a traceable pathway to market. Green development in this sense is not a separate project added after mechanization. It emerges when mechanization is used to raise the efficiency of the whole chain and to reduce wasted labor, wasted grain, and wasted operations.

5 Case Analysis of Mechanization Application in Mashan Agricultural Service Center

Before discussing the individual cases, one limitation should be stated clearly. The four cases below are based mainly on two internal project briefs supplied with the manuscript materials and on field photographs (Table 2). These are operational management materials rather than independently audited datasets. They are therefore used here as descriptive case evidence, not as a statistical basis for causal inference. Their value lies in showing how the center works in practice.

Table 2 Core operational cases from Mashan Agricultural Service Center

Case	Main content	Practical significance
Centralized seedling cultivation services	More than 200,000 seedling trays supplied annually; technical guidance reportedly improved seedling establishment by about 20%	Strengthens the basis for machine transplanting and reduces household nursery burden
Emergency mechanized harvesting during "double rush"	More than 20 harvester operations deployed; over 12,000 mu harvested; over 14,000 tons dried	Demonstrates disaster-response and harvest-loss-reduction capacity
Grain drying capacity improvement	Eight dryers added; batch capacity raised to 400 tons; annual drying increased from 10,000 to 18,000 tons	Converts mechanized harvesting into stable postharvest management
High-quality rice brand development	"Xinfeng" rice won Silver Award in "Zhejiang Good Rice 2024"	Connects mechanized services with local branding and value-added products

5.1 Case of centralized seedling cultivation services

The centralized seedling cultivation case is important because it shows how a service center can intervene at the earliest and often most fragile stage of rice production. According to the case materials, Mashan relies on its seedling cultivation center and mechanized sowing arrangements to provide unified seedling services for surrounding farmers, supplying more than 200,000 seedling trays annually. This is not a small support activity attached to the center. It is one of the enabling conditions of full-process mechanization.

The practical effect of such a service is straightforward. Farmers who receive standardized tray seedlings do not need to manage seedling preparation individually at household scale. That lowers labor requirements, reduces technical unevenness across farms, and makes machine transplanting easier to schedule. The internal materials further note that technical guidance linked to the center helped raise seedling establishment rates by around 20%, which suggests that the service is not purely material supply, but a combination of production input and agronomic support.

This case also reflects conclusions from recent agricultural mechanization studies. Research has shown that centralized seedling cultivation not only supports machine transplanting but also improves seedling-field efficiency and helps release land and labor resources under crop rotation systems (Ruan et al., 2025). In the Mashan case, the local lesson is simpler but equally important: professionalized seedling supply makes later mechanized stages more reliable and improves the overall rhythm of rice production.

5.2 Case of mechanized emergency harvesting during the "Double Rush" period

Among the four cases, the emergency harvesting case most clearly demonstrates the social value of regional agricultural service centers. During the overlap of the "double rush" farming season and typhoon weather, Mashan mobilized more than 20 harvester operations, completed emergency harvesting on more than 12,000 mu of early rice, and carried out more than 14,000 tons of grain drying afterward. The combination of harvesting and drying is especially important.

What makes this case analytically meaningful is not only the scale, but also the timing. During normal years, mechanization improves production efficiency. During abnormal years, it protects grain that has already been produced. Research on rice harvest losses repeatedly emphasizes that poor harvest management and weak infrastructure can significantly increase grain losses, while timely harvesting is one of the most important conditions for effective loss reduction (Qu et al., 2021). The Mashan case transforms this general conclusion into a concrete operational example. Harvesting machines alone would not have solved the problem. Without sufficient drying capacity, much of the rescued grain would still have remained vulnerable under humid conditions.

This case also aligns closely with Zhejiang Province's agricultural modernization policy. Zhejiang's 2024 policy documents specifically encouraged modern agricultural service centers to establish emergency operation teams and participate in regional agricultural disaster-response systems. Therefore, Mashan's emergency harvesting activities should not be viewed simply as a temporary operational success. Instead, they represent the kind of regional resilience function that current agricultural policy increasingly expects from modern service infrastructure.

5.3 Case of grain drying capacity improvement

The drying-capacity expansion case demonstrates that the development path of the Mashan center gradually moved from basic agricultural service provision toward stronger postharvest management capacity. According to the project materials, the center added eight grain dryers during expansion, increasing single-batch drying capacity to 400 tons and annual drying capacity from 10,000 tons to 18,000 tons. The center also added a 750-ton indoor metal grain warehouse and a 50-ton rice processing line.

This case matters because drying is one of the clearest dividing lines between partial mechanization and full-process mechanization. A mechanized production system without adequate drying facilities still faces substantial quality and storage risks. High-moisture grain cannot remain untreated for long periods under humid climatic conditions. Furthermore, for high-quality rice, standardized drying is itself an important part of quality preservation. Recent drying studies have shown that better control of drying process parameters can improve the balance between drying efficiency and grain quality retention (Li et al., 2024).

The practical importance of Mashan's drying expansion is therefore twofold. First, it strengthens regional grain-loss reduction and grain-storage security capacity. Second, it makes downstream rice processing and branding more reliable. Quality-oriented rice production requires consistency not only in the field, but also after harvest. By expanding drying and storage capacity, the center created a stronger bridge between emergency harvest rescue, grain quality retention, and value-added rice products.

5.4 Case of high-quality rice brand development

The fourth case extends the analysis from agricultural production and service provision to market value creation. The internal project materials state that Mashan registered the "Xinfeng" rice brand, and that the brand won the Silver Award in the "Zhejiang Good Rice 2024" competition. Although this result is not a production indicator in the narrow agronomic sense, it remains a meaningful applied outcome. A service center that can supply seedlings, organize mechanized operations, coordinate drying, and process grain is naturally in a stronger position to support stable branded rice products than a service provider limited only to field operations.

The significance of this case becomes clearer when viewed within Zhejiang's provincial rice-branding framework. The "Zhejiang Good Rice" program evaluates rice not only on yield, but also on grain quality, eating quality, safety indicators, and standardized production records. In other words, brand recognition is closely tied to production organization and traceability rather than marketing language alone. Under such a policy environment, the Mashan case suggests that full-process mechanization can contribute not only to production efficiency and grain-loss reduction, but also to the market differentiation and added value of locally produced high-quality rice.

More broadly, this case reflects a larger transition in the role of regional agricultural service centers. Their function is no longer limited to "helping farmers complete field operations." Increasingly, they are also becoming important platforms for product upgrading, local branding, and value-chain extension. This transition is particularly important in developed eastern provinces, where agriculture often needs to rely on quality, service integration, and branding rather than low-cost bulk production alone.

6 Current Problems

6.1 High investment costs of advanced agricultural machinery

One of the clearest constraints revealed by the Mashan case is the high capital intensity required for full-process mechanization. The internal materials describe more than RMB 6 million in project investment, around RMB 8 million in machinery assets, as well as large-scale drying facilities, nursery infrastructure, grain storage systems, and a rice processing line. Although this structure provides strong operational support for modern rice production, it also explains why many smaller organizations and ordinary farming households cannot easily replicate such a model independently.

Existing research supports this concern. Studies on agricultural mechanization and grain production efficiency in China have repeatedly shown that although machinery can improve productivity and operational efficiency, high acquisition and upgrading costs remain major barriers, especially in regions characterized by small farm sizes and uncertain returns (Liu and Li, 2023; Li et al., 2024). Advanced grain dryers, intelligent transplanting systems, plant-protection machinery, and digital management equipment require not only initial investment, but also continuous expenditures for maintenance, fuel, electricity, repair, and replacement.

For Mashan Agricultural Service Center, this means that future development depends on maintaining a balance among policy support, service income, and operational scale. If service demand decreases, it becomes more difficult to absorb high fixed costs. Conversely, if machinery technology upgrades too quickly relative to local service revenues, the center may face financial pressure despite maintaining advanced equipment. Therefore, capital intensity is not simply an issue of investment; it is also a long-term issue of operational sustainability.

6.2 Shortage of professional agricultural machinery technicians

The Mashan materials indicate that the center currently employs seven full-time workers and maintains a 100% certification rate among machinery operators. While this reflects a relatively standardized management structure, it also reveals an important vulnerability. A limited number of technical personnel are expected to support multiple services simultaneously, including seedling cultivation, machinery dispatching, machinery maintenance, pest-control coordination, grain drying, storage management, and farmer training.

As agricultural service systems become more integrated and digitalized, the demand is no longer limited to machine operators alone. Service centers increasingly require multi-skilled technicians capable of managing scheduling systems, field operations, equipment repair, drying control, safety supervision, operational records, and digital agricultural platforms.

This issue has already been recognized in recent agricultural modernization research. Studies on smart agricultural machinery and digital farming systems show that many service organizations still face barriers related to technical training, digital literacy, management ability, and operational competence (Gong et al., 2024; Hashim et al., 2024; Li et al., 2024). The effectiveness of advanced agricultural machinery does not depend solely on subsidies or equipment ownership. It also depends heavily on whether operators and service personnel can use the technology effectively under practical farming conditions.

For Mashan, this suggests that human-resource limitations may become the next major bottleneck after machinery investment. Even well-equipped service centers may struggle to achieve their expected efficiency if they lack enough qualified personnel capable of operating, maintaining, and coordinating modern agricultural systems. As the center moves toward more quality-oriented and digitalized production models, the importance of technical talent will continue to increase.

6.3 Differences in mechanization levels among small-scale farmers

Although regional agricultural service centers can reduce inequality in technology access, they cannot completely eliminate differences among farmers. In practice, smallholder farms still differ greatly in land fragmentation, road accessibility, irrigation conditions, willingness to pay for services, awareness of quality-oriented production, and acceptance of standardized farming management.

Research on agricultural socialized services in China has consistently shown that service outcomes vary according to regional conditions, land fragmentation levels, and household characteristics. Farmers with stronger production orientation, lower land fragmentation, or higher digital capability often benefit more quickly from mechanized services (Liao et al., 2025; Zeng et al., 2025).

This issue is particularly relevant in the Mashan case because the center serves both nearby villages and a broader multi-township agricultural region. As the service radius expands, the center inevitably encounters greater variation in field conditions and farmer demands. A single standardized service package may therefore not suit all users equally well. Some households may only purchase harvesting services, while others may accept partial or full-process trusteeship services. Some farmers prioritize quality-oriented branded production, whereas others focus mainly on reducing immediate production costs.

These differences indicate that full-process mechanization still has organizational and social boundaries. Even when machinery services are available, farmer adoption depends on factors such as trust, land conditions, production goals, and the suitability of service arrangements. Therefore, agricultural service centers must function not only as technical providers, but also as coordinators capable of matching different farmers with appropriate service combinations.

6.4 Significant impacts of extreme weather on rice production

The Mashan emergency harvesting case clearly demonstrates that extreme weather remains a major challenge even in relatively well-equipped agricultural regions. Rice production in China is increasingly exposed to climatic uncertainty, including heat stress, heavy rainfall, typhoon events, and humid harvesting conditions. Recent climate-related studies suggest that extreme climate events may become more frequent and more severe in future rice production systems, particularly under warming scenarios that intensify heat stress and increase production instability (Jiang et al., 2025).

For agricultural service centers, extreme weather creates several interconnected challenges. It shortens operational windows, increases pressure on machinery scheduling, raises demand for emergency drying and temporary storage, and may generate sudden service demand beyond ordinary operational capacity. Mashan’s ability to organize emergency harvesting and large-scale drying during the “double rush” period was impressive, but the case also reveals how quickly even well-organized systems can be placed under stress during abnormal climatic conditions.

This challenge is unlikely to disappear in the future. Modern agricultural service centers will increasingly be evaluated not only by their efficiency during normal seasons, but also by their resilience during periods of climatic disruption. Full-process mechanization improves regional response capacity, but resilience itself must now become an explicit goal in the design of agricultural modernization systems.

7 Optimization Suggestions and Development Directions

7.1 Improving the regional agricultural machinery service system

The Mashan case suggests that the future development of agricultural mechanization depends not simply on increasing the number of machines, but on strengthening the regional agricultural service system itself. Zhejiang Province’s 2024 policy already reflects this direction by emphasizing layered service networks, comprehensive functional coverage, and the establishment of a five-kilometer agricultural service circle. For service centers such as Mashan, the practical implication is the establishment of clearer service zoning, including a nearby core area for highly intensive “nanny-style” services, a broader operational area for scheduled cross-township services, and an emergency-response layer designed for extreme weather and urgent harvesting tasks.

Recent research also supports stronger integration of agricultural service systems. Studies on agricultural socialized services show that service efficiency is highest when mechanized operations improve production continuity, operational coordination, and machinery utilization across different stages of farming (Cai et al., 2024; Liao et al., 2025). Instead of expanding services randomly, agricultural service centers should strengthen the links among seedling cultivation, transplanting, plant protection, harvesting, drying, transportation, and storage so that farmers can rely on one coordinated operational chain rather than fragmented service providers.

For Mashan, this may involve establishing more stable long-term service agreements with nearby villages, improving seasonal booking systems, and strengthening coordination among grain ordering, drying demand, and emergency operation planning. The long-term objective is not merely to remain a capable service provider, but to become a stable regional agricultural operation hub.

7.2 Strengthening agricultural machinery training and talent cultivation

Machinery-centered modernization cannot be sustained if talent development falls behind infrastructure construction. Mashan Agricultural Service Center already provides technical guidance and training spaces, which creates a strong foundation for future development. However, the next step should be to shift from occasional training activities toward a more systematic and layered talent cultivation framework.

Current research provides clear evidence for the importance of training and technical capacity building. Studies on smart agricultural machinery adoption and digital agricultural transformation indicate that technology adoption depends heavily on practical training, demonstration effects, operator confidence, and digital literacy (Gong et al., 2024; Hashim et al., 2024; Li et al., 2024). Advanced machinery alone cannot improve agricultural modernization unless users understand how to operate, maintain, and coordinate the technology effectively under real production conditions.

For Mashan, a tiered training system would be particularly useful. The first level should focus on safe and standardized machinery operation. The second level should emphasize quality-oriented field management, drying control, and postharvest handling. The third level should target younger agricultural workers, cooperative members, and local service-team leaders who are capable of combining agricultural technology with management and digital skills. Such a training structure would also align closely with Zhejiang Province’s policy emphasis on cultivating practical agricultural talent through modern agricultural service centers.

7.3 Promoting green and intelligent agricultural machinery

The future green transformation of rice production increasingly depends on “intelligent enough” agricultural machinery rather than simply larger machinery. For Mashan Agricultural Service Center, the key issue is not whether to adopt intelligent technologies, but which technologies provide the highest practical value under local production conditions.

Recent research provides several important directions. Studies on UAV-based plant protection show that precision spraying systems can improve operational timeliness, reduce labor burden, and lower operator exposure while still maintaining effective pest-control performance under suitable conditions (Paul et al., 2024). Smart-farming studies in rice production also emphasize the value of integrating sensors, IoT systems, and digital decision-support tools into irrigation management, crop monitoring, and quality management systems (Hashim et al., 2024). In addition, grain-drying research has shown that improved drying-control systems can significantly improve grain quality retention and reduce postharvest losses (Li et al., 2024).

For Mashan, the most appropriate strategy is therefore to prioritize “practical intelligence” rather than blindly pursuing expensive technologies with limited local applicability. In practical terms, technologies that directly improve operation timing, quality consistency, or grain-loss reduction should receive priority. Precision plant-protection equipment, drying parameter monitoring systems, and machinery scheduling platforms are likely to provide more immediate value than highly complex systems that require excessive investment and technical support.

7.4 Enhancing digital and information-based management

If the first stage of modern agricultural service center development focused mainly on physical infrastructure construction, the second stage increasingly focuses on digital and information-based management. Zhejiang Province’s 2024 agricultural modernization policy explicitly encourages integration with provincial digital agriculture platforms and supports the establishment of online-offline integrated agricultural service systems. This policy direction is particularly relevant for Mashan because the center already manages multiple agricultural functions across a relatively large regional service area.

Digital management can significantly improve coordination among seedling supply, machinery dispatch, harvesting schedules, drying queues, service records, and grain traceability systems. Recent studies on digital agricultural service systems show that digital tools can increase farmers' willingness to adopt modern agricultural technologies by improving information accessibility, strengthening technical understanding, and reducing communication barriers (Gong et al., 2024). Smart-farming research in rice systems likewise demonstrates that digital technologies are becoming increasingly important for crop monitoring, yield estimation, classification management, and production decision support (Hashim et al., 2024).

For Mashan, digital transformation does not necessarily need to begin with highly complex artificial intelligence systems. A more practical approach would be to begin with relatively simple but operationally useful digital tools, including online booking systems for transplanting and harvesting, machinery scheduling records, drying-batch monitoring, grain traceability systems, and farmer service databases. Once these systems become stable and widely accepted, the center could gradually expand toward more advanced digital support systems for quality management, emergency coordination, and regional agricultural decision-making. In high-quality rice production systems, traceability itself has already become an important source of product value.

8 Conclusion

This study used Mashan Agricultural Service Center in Shangyu District as a practical case to examine how full-process mechanization can support the green and efficient production of high-quality rice. The case shows that the real strength of full-process mechanization does not lie in any single machine or single operation. Its strength lies in coordination. When centralized seedling cultivation, machine transplanting, organized field management, plant protection, combine harvesting, grain drying, storage, and simple processing are linked into one service system, rice production becomes more timely, more stable, and better able to protect both yield and quality.

The Mashan experience also shows that regional agricultural service centers have become important institutions in the modernization of rice production. They reduce barriers facing small farmers, expand access to modern technology, improve emergency response during extreme weather, and create the practical conditions for branded high-quality rice development. The center's case is especially valuable because it connects policy goals with operational reality: it demonstrates how a local service platform can turn broad ideas such as green production, socialized service, and agricultural modernization into concrete field practices.

At the same time, the case makes clear that further progress will depend on solving several structural problems, including high capital costs, shortage of professional technicians, unequal service uptake among farmers, and weather-related risk. For that reason, the future direction of Mashan and similar centers should emphasize stronger regional service networks, training-oriented talent cultivation, useful intelligent equipment, digital management, and deeper integration of the rice industry chain. If these directions are pursued steadily, full-process mechanization can continue to serve not only as a labor-saving production model, but also as a realistic pathway toward higher quality, lower loss, greener operation, and more resilient rice agriculture.

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Research Article Open Access

Polygenic Risk Scores (PRS/PGS) across Multi-ancestry and Cross-domain Settings: Statistical Framework, Methodological Advances, and Robustness Evaluation

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Abstract Polygenic risk scores (PRS/PGS) aggregate genome-wide association study (GWAS) effect sizes to quantify individual-level genetic susceptibility, serving as a key bridge between genetic association findings and practical applications. With the rapid expansion of large-scale genotype-phenotype datasets, PRS methodology has evolved from early clumping-and-thresholding (C+T) approaches to frameworks that explicitly model linkage disequilibrium (LD) and effect size distributions using Bayesian shrinkage and penalized regression, and further incorporate functional annotations, multi-ancestry data, and transfer learning to improve predictive performance and interpretability. However, the portability and robustness of PRS across populations remain major challenges, often manifesting as reduced predictive accuracy, calibration bias, and unstable decision thresholds. From a statistical perspective, these issues can be understood as an estimand mismatch arising from differences in LD structure, allele frequency spectra, and effect distributions across populations. In this study, we revisit PRS within a unified statistical genetics framework by conceptualizing it as a model-dependent predictive functional, and link it to SNP heritability as part of a continuous inference chain from variance decomposition to individual-level prediction. Building on this perspective, we systematically review and compare state-of-the-art PRS methods under multi-population settings, including LD-aware Bayesian shrinkage, functionally informed models, multi-ancestry transfer learning, and model stacking and recalibration strategies, with representative methods such as PRS-CSx, CT-SLEB, and PolyPred. We further propose a standardized analytical workflow of “training-validation-freezing-external evaluation” and advocate a multi-dimensional evaluation framework based on relative R^2/AUC, calibration metrics, and decision-curve net benefit. In addition, we discuss joint modeling of PRS with environmental and lifestyle factors and its applications in both human health and crop breeding. Finally, we address issues of cross-population inequity and ethical governance, and propose an integrated framework centered on multi-ancestry data expansion, causal and functional annotation integration, ancestry-aware modeling, environment coupling, and population-specific recalibration. This framework aims to promote PRS/PGS from a predictive tool toward a transferable, interpretable, and equitable decision-support system, providing a systematic foundation for the application of complex trait genetics.

Keywords Polygenic risk scores; Statistical genetics; SNP heritability; Cross-population prediction; Linkage disequilibrium; Bayesian shrinkage; Transfer learning; Gene-environment interaction; Fairness

Polygenic risk scores (PRS/PGS) aggregate effect size estimates derived from genome-wide association studies (GWAS) to generate individual-level predictions, thereby transforming locus-trait associations into quantitative measures of genetic susceptibility for complex traits or diseases. With the continuous expansion of large-scale genotype-phenotype cohorts and advances in computational methods, PRS construction has evolved from early clumping-and-thresholding (C+T) approaches to frameworks that explicitly model linkage disequilibrium (LD) and effect size sparsity using Bayesian shrinkage and penalized regression. More recently, these methods have further incorporated functional annotations, fine-mapping, and multi-trait information to enhance signal-to-noise ratio, interpretability, and predictive performance. This methodological progression reflects a paradigm shift in statistical genetics from hypothesis-driven analyses to genome-wide, hypothesis-free scanning (Cai et al., 2021; Weissbrod et al., 2022; Zhang et al., 2023; Fang and Wu, 2026). Meanwhile, multi-ancestry training and cross-population transfer learning approaches have rapidly developed, and the increasing availability of open-access GWAS summary statistics and LD reference panels has facilitated reproducibility, cross-platform application, and secondary analyses (Wang et al., 2023).

Across both human medicine and crop breeding, PRS/PGS share a fundamentally analogous objective: to enable early prediction, risk stratification, and selection decisions at the individual level under resource constraints. In medical research, PRS provides a relatively stable estimate of genetic risk across the life course beyond traditional risk factors, supporting stratified screening, longitudinal monitoring, and personalized intervention (Lennon et al., 2024; Xiang et al., 2024). In crop breeding, PGS is methodologically aligned with genomic selection, and is particularly valuable for traits that are costly or late to measure (e.g., perennial crops or complex stress-related traits), where it can serve as an early surrogate phenotype for individual selection, parental optimization, and cross prediction, thereby increasing genetic gain per unit time or cost (Sima et al., 2024). Consequently, establishing a unified methodological language and evaluation framework across medicine and breeding has become an important direction for advancing the application of statistical genetics.

Despite continuous methodological and data advances, the portability and robustness of PRS/PGS across populations remain major challenges. Predictive performance is highly dependent on the allele frequency spectrum and LD structure of the training population. When LD patterns and the tagging relationships between SNPs and causal variants differ across ancestries, signal attenuation or effect size distortion commonly occurs during extrapolation. In addition, population-specific effects, gene-environment interactions, and heterogeneity in phenotype definition and measurement further contribute to reduced explanatory power, calibration bias, and instability of decision thresholds. From a statistical inference perspective, these issues can be understood as an estimand mismatch arising from differences in LD structure, allele frequency spectra, and effect distributions across populations (Duncan et al., 2019; Jayasinghe et al., 2024; Fang, 2026). This structural bias manifests consistently across both human and agricultural systems and extends to concerns regarding population fairness and practical implementation. Moreover, imbalances in sample size and resource availability across ancestries exacerbate the underperformance of PRS in underrepresented populations, making cross-population PRS applications a complex challenge involving statistical modeling, data infrastructure, and ethical governance.

Under this context, it is necessary to re-examine the nature of PRS/PGS from a statistical inference perspective. Strictly speaking, PRS is not a direct estimate of “true genetic risk,” but rather a model-dependent predictive functional defined by the training data, LD structure, and effect estimation model. This perspective is intrinsically consistent with the statistical interpretation of SNP heritability (Fang, 2026): the latter quantifies the proportion of phenotypic variance explained by additive genetic effects under a given set of markers and model assumptions, whereas PRS projects this genetic signal into an individual-level predictive quantity under the same informational constraints. In other words, SNP heritability reflects variance explained at the population level, whereas PRS reflects predictive ability at the individual level, together forming a continuous inference chain from variance decomposition to individual prediction.

Within this unified framework, differences among PRS methods (e.g., C+T, LD-aware Bayesian shrinkage, and multi-ancestry transfer models) fundamentally correspond to different modeling assumptions regarding effect size distributions, LD structure, and sparsity, thereby implying different statistical targets (estimands). Consequently, PRS performance depends not only on sample size and data quality, but also on the degree of alignment between model assumptions and the target population. The decline in cross-population predictive performance can thus be interpreted as a manifestation of estimand mismatch at the level of individual prediction.

Building on this perspective, the present study focuses on the “individual prediction layer” within the broader framework of statistical genetics, extending prior work on methodological paradigm evolution (Fang and Wu, 2026) and variance-based inference (Fang, 2026). We systematically review and compare state-of-the-art PRS/PGS methods in multi-population contexts, including cross-ancestry effect estimation and transfer learning, ancestry-aware LD modeling, functional annotation and causal refinement, as well as model stacking and recalibration strategies, with representative methods such as PRS-CSx, CT-SLEB, and PolyPred. At the level of evaluation and practice, we propose a standardized workflow of "training-validation-freezing-external evaluation," emphasizing a multi-dimensional assessment based on relative R^2/AUC, calibration slope, and decision-curve net benefit. This framework is further complemented by ancestry-stratified and LD-perturbation sensitivity analyses, small-sample recalibration in target populations, and cost-benefit evaluation, supported by benchmark datasets, reference panels, and transparent reporting standards, with the aim of promoting the development of PRS/PGS as a transferable, interpretable, and equitable tool for applications in human health and crop improvement.

1 Fundamental Framework and Methodological Evolution of PRS/PGS

From a statistical inference perspective, the construction of PRS/PGS can be understood as a process that translates population-level association signals into individual-level predictive quantities. Specifically, the marginal effect estimates obtained from GWAS are not directly suitable for prediction; instead, they must be re-estimated under appropriate modeling assumptions that account for linkage disequilibrium structure and effect size distributions. This typically involves shrinkage and aggregation procedures that yield more stable and generalizable effect representations. These regularized effects are then projected onto individual genotype profiles to quantify genetic risk at the individual level. In this sense, PRS can be viewed as a model-dependent predictive function, jointly determined by effect estimation, regularization strategies, and genotype encoding, reflecting a continuous inferential pathway from association signal extraction to individual risk prediction.

Differences among methods fundamentally arise from distinct modeling assumptions regarding effect size distributions, linkage disequilibrium (LD) structure, and sparsity, thereby implying different statistical targets (estimands). Under this framework, the evolution of PRS methodology can be understood as a progression from "independent locus approximation" to "LD-aware modeling," and further toward the integration of functional and ancestry information.

1.1 Classical clumping and thresholding (C+T)

Clumping and thresholding (C+T) is one of the earliest and most widely used approaches for constructing PRS/PGS (Sima et al., 2024) (Figure 1). This method begins with single-marker GWAS effect estimates, ranks candidate variants by statistical significance (p-values), and performs LD clumping using predefined window sizes and r^2 thresholds to retain representative "sentinel" SNPs. Individual scores are then calculated via linear aggregation:

$$PRS_i = \sum_{m=1}^{M} \beta_m x_{im}$$

where β_m denotes the marginal effect size of the m-th SNP, and x_{im} represents the genotype of individual i. From a statistical modeling perspective, the C+T approach can be interpreted as a sparse estimation strategy that performs variable selection through hard thresholding. Under this framework, only variants exceeding a predefined significance threshold are retained, implicitly approximating the genetic architecture of a trait as being driven by a limited number of loci with relatively large effects. While this formulation simplifies the model structure, it also entails a substantial reduction of correlation information among variants. In practice, achieving a balance between model simplicity and predictive performance typically requires systematic exploration across a range of significance thresholds and linkage disequilibrium parameters, with model selection guided by validation data to identify an appropriate parameter configuration.

C+T offers advantages including simplicity, low computational cost, direct compatibility with GWAS summary statistics, and strong interpretability, making it a useful baseline method or rapid screening tool for large-scale traits (Wang et al., 2023). However, its "hard" LD pruning discards potentially informative variants and prevents optimal weighting within LD blocks. Moreover, its sensitivity to threshold selection and reference panels often leads to poor transferability across populations (Jayasinghe et al., 2024; Kachuri et al., 2024). Fundamentally, this reflects substantial shifts in the estimand when LD structure is ignored in cross-population settings.

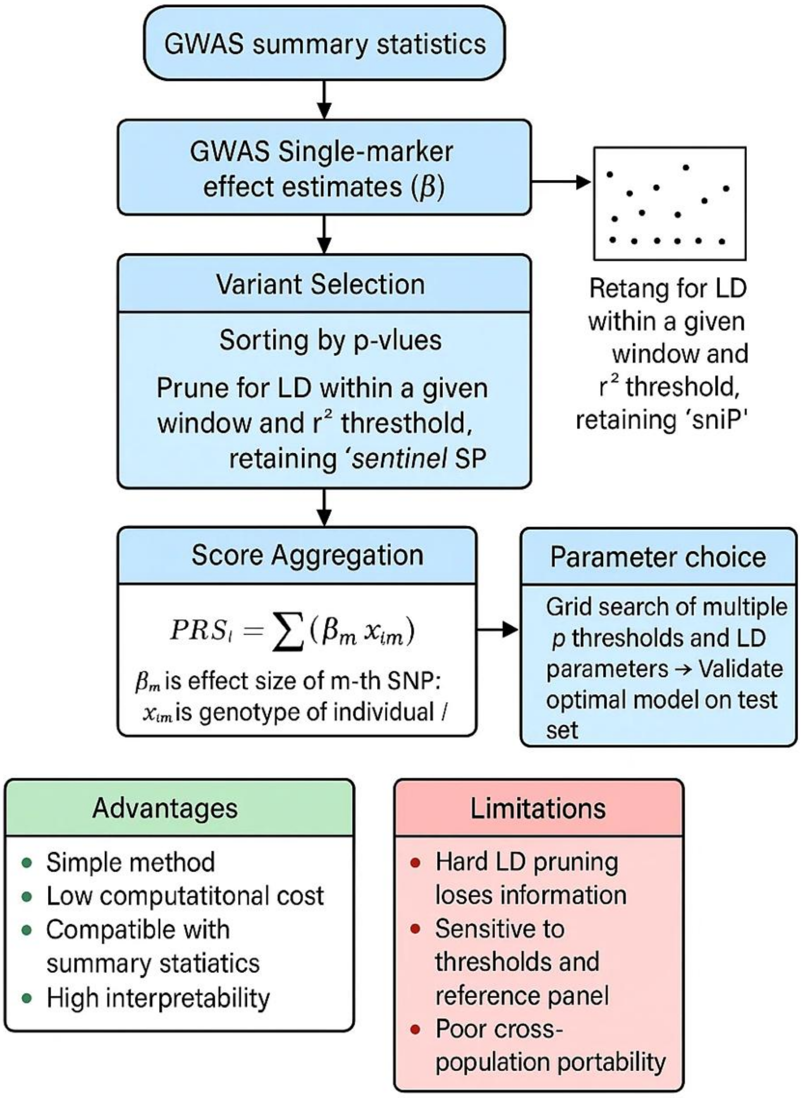

Figure 1 Workflow of the clumping and thresholding (C+T) approach for constructing polygenic risk scores (PRS)

Note: This figure illustrates the standard workflow of the clumping and thresholding (C+T) method for constructing polygenic risk scores (PRS). Starting from GWAS summary statistics, single-marker effect estimates (β) are obtained and used for variant selection. SNPs are first ranked by statistical significance (p-values), followed by linkage disequilibrium (LD)-based clumping within a specified genomic window and r^2threshold, retaining representative "sentinel" variants while removing correlated markers. The selected variants are then aggregated into an individual-level PRS using a linear scoring function, where SNP effect sizes serve as weights and individual genotypes as predictors. Model parameters, including p-value thresholds and LD pruning criteria, are typically optimized via grid search in a validation dataset

The C+T approach is computationally efficient, interpretable, and compatible with GWAS summary statistics, making it a widely used baseline method. However, its reliance on hard LD pruning may discard informative variants and lead to suboptimal weighting within LD blocks. In addition, the method is sensitive to parameter choices and LD reference panels, which limits its portability across populations.

1.2 LD-aware and bayesian methods

To overcome the limitations of C+T in handling LD, methods that explicitly model LD structure have been developed, including LDpred, LDpred2, and PRS-CS (Weissbrod et al., 2022). These approaches incorporate an LD matrix $R$from a reference panel and jointly estimate SNP effects via de-correlation and shrinkage, aiming to obtain the posterior expectation:

$$\mathbb{E}(\beta \mid \hat{\beta}, R)$$

At the modeling level, different approaches distinguish themselves primarily through the choice of prior distributions imposed on effect sizes, thereby reflecting distinct assumptions about the underlying genetic architecture. For instance, the LDpred family of methods typically adopts a point-normal mixture prior to explicitly capture sparsity in effect sizes, whereas PRS-CS employs a continuous shrinkage prior that allows effect sizes to vary more smoothly across the genome and enables data-driven estimation of global hyperparameters (Sima et al., 2024). These differences in prior specification fundamentally represent alternative trade-offs between sparsity and continuity in modeling genetic effects.

From a unified statistical perspective, these methods can be expressed as:

$$\hat{\beta} = \text{shrinkage}(\beta, LD, prior)$$

That is, regularized estimation of GWAS effects under LD constraints and prior assumptions. Compared to C+T, these approaches avoid discrete LD pruning and instead achieve near-optimal linear combinations within LD regions, typically resulting in improved predictive performance and greater parameter stability.

However, their performance depends critically on the consistency between the LD reference panel and the target population. When ancestry mismatch or structural variation exists, LD discrepancies may bias effect estimation and degrade prediction accuracy (Jayasinghe et al., 2024). In addition, large-scale LD matrix computation imposes substantial computational burden, and although methods such as LDpred2 have improved efficiency, trade-offs between accuracy and scalability remain.

1.3 Functional annotation and prior integration

To better approximate causal variants and reduce “tagging effects,” recent methodological advances have incorporated functional annotation information into effect estimation. Stratified LD score regression (S-LDSC) estimates heritability contributions across annotation categories within the baseline-LD framework, providing a basis for constructing informative priors (Sima et al., 2024).

Representative methods such as AnnoPred and LDpred-funct integrate functional annotations into Bayesian priors, assigning higher inclusion probabilities or weaker shrinkage to biologically relevant variants (e.g., eQTLs or open chromatin regions), thereby improving signal-to-noise ratio and predictive performance. Because some functional annotations are relatively conserved across populations, these approaches can partially mitigate cross-population bias induced by differences in LD structure and allele frequencies.

From a statistical modeling perspective, the incorporation of functional annotations can be viewed as integrating external biological information into the effect estimation process. This is typically achieved by imposing structured priors that differentiate across variant categories, thereby enabling a more structured representation of effect size distributions. As a result, the model no longer relies solely on data-driven estimation, but instead leverages prior information to guide shrinkage, improving both signal detection and estimation stability.

However, functional annotations are often tissue-and environment-specific and subject to measurement and annotation biases, which may lead to prior misspecification. Therefore, in practice, multi-tissue integration and small-sample recalibration in the target population are recommended to enhance robustness (Jayasinghe et al., 2024).

1.4 Multi-ancestry transfer and cross-population models

The primary objective of multi-ancestry PRS is to balance sample size and genetic heterogeneity across populations by jointly leveraging GWAS data from multiple ancestries and ancestry-specific LD structures, thereby improving generalization performance (Ruan et al., 2021; Zhang et al., 2023). For example, PRS-CSx performs continuous shrinkage separately within each ancestry and integrates results using shared hyperparameters and data-driven weights, capturing both shared and population-specific effects (Sima et al., 2024).

In addition, transfer learning and meta-GWAS approaches are widely used. Heterogeneity-aware meta-analysis and random-effects models can reduce estimation bias across studies, while stacking or reweighting methods can be applied when target population data are limited, enabling recalibration and adaptation of multiple ancestry-specific scores (Cai et al., 2021; Gunn et al., 2024).

Within a unified statistical framework, multi-ancestry approaches can be viewed as mechanisms for integrating and reconstructing the underlying estimands across populations. Rather than simply pooling data from multiple sources, these methods recharacterize the target estimand by balancing shared genetic effects against population-specific heterogeneity, typically through weighting schemes or hierarchical modeling. This allows the resulting predictive function to better accommodate cross-population variation.

The core challenge lies in accommodating differences in LD structure, allele frequency spectra, and effect heterogeneity across populations. In practice, this requires ancestry inference, local LD similarity assessment, and frequency-aware weighting of training data. Evaluation should include relative R^2/AUC, calibration metrics, and decision-curve net benefit in the target population to comprehensively assess portability (Jung et al., 2025).

1.5 Relationship between PRS and SNP heritability: a unified view of variance explanation and individual prediction

Within the statistical genetics framework, PRS and SNP heritability are not independent quantities but rather complementary representations of the same underlying genetic information at different levels. SNP heritability is typically defined as the proportion of phenotypic variance explained by additive genetic effects captured by a given set of markers under specific model assumptions, representing a population-level variance decomposition. In contrast, PRS aggregates these effects into an individual-level predictive function that quantifies relative genetic risk.

Theoretically, the predictive performance of PRS is bounded by SNP heritability. Under ideal conditions-unbiased effect estimation, perfectly matched LD structure, and infinite sample size-PRS can approach the maximum variance explained by SNP heritability. In practice, however, PRS performance is typically lower due to estimation error, LD mismatch, and shrinkage-induced bias. Therefore, PRS performance should not be interpreted as a direct measure of trait heritability, but rather as an indicator of how effectively genetic signals can be identified and utilized under given data and model constraints.

This relationship can be formalized as a variance-prediction duality in statistical genetics (Fang, 2026): SNP heritability quantifies variance explained at the population level, whereas PRS reflects predictive ability at the individual level. The former corresponds to variance component estimation in random-effects models, while the latter corresponds to predictive functions constructed under shrinkage and regularization. Although both are theoretically linked through effect size distributions and LD structure, they often correspond to different estimands in practice due to differences in model assumptions and data structures.

This perspective is particularly important for understanding cross-population prediction. When allele frequency spectra, LD structure, or effect distributions differ across populations, both SNP heritability and PRS estimands may change, with PRS being more sensitive due to its dependence on specific effect estimates and LD modeling. Thus, the decline in cross-population predictive performance can be viewed as a manifestation of estimand mismatch at the level of individual prediction.

Based on this understanding, both PRS construction and evaluation should explicitly consider its relationship with SNP heritability. On the one hand, heritability estimates provide a theoretical upper bound and reference for PRS performance; on the other hand, improvements in effect estimation, ancestry-aware LD modeling, and target-specific recalibration are essential to narrow the gap between PRS performance and its theoretical limit, thereby enhancing predictive accuracy and cross-population portability.

2 Training-Validation-External Generalization Workflow

From a statistical inference perspective, the construction and evaluation of PRS/PGS should follow a staged process of estimation-regularization-prediction-validation, with the core objective of obtaining a stable and interpretable predictive function for the target population while avoiding overfitting. This workflow not only involves data partitioning and model selection, but also directly relates to the definition of the statistical target (estimand) and its consistency across different data domains.

2.1 Data splitting and internal validation

To ensure unbiased model development and evaluation, a three-stage framework is typically adopted: training, validation, and testing sets. The training set is used for effect estimation and model fitting; the validation set is used for hyperparameter tuning and recalibration (e.g., p-value thresholds, shrinkage strength, and global scaling factors); and the test set is reserved for one-time performance evaluation (Sima et al., 2024). This process corresponds to the “effect size → shrinkage → PRS” stage in the statistical inference pipeline and represents the key point at which model bias enters.

In both human genetics and crop breeding contexts, particular attention must be paid to sample structure dependence. Related individuals (e.g., families, lines, or close relatives) should be assigned to the same data split to avoid information leakage. At the same time, the distribution of phenotypes and key covariates (e.g., sex, batch effects, ancestry principal components) should be comparable across splits. For studies with limited sample sizes, nested cross-validation or leave-group-out strategies (e.g., by population, environment, or experimental site) can improve estimation stability and reduce selection bias (Lennon et al., 2024).

In the preprocessing stage, genotype-phenotype harmonization must be strictly reproducible, including alignment of reference alleles and genomic coordinates, removal of ambiguous variants, and the use of LD reference panels and allele frequency estimates matched to the target population. Different methods reflect distinct modeling assumptions in their tuning strategies: C+T relies on grid search over p-value thresholds and LD parameters, whereas LD-aware and Bayesian approaches adjust prior strength or LD block structure for shrinkage estimation (Wang et al., 2023; Sima et al., 2024). During validation, only linear recalibration (e.g., slope and intercept adjustment) should be permitted. Once the model is frozen, any form of re-tuning (“information leakage”) must be strictly avoided to ensure independence of testing and external evaluation.

2.2 External generalization and cross-population evaluation

External generalization is the core step in evaluating PRS portability. It is fundamentally a statistical inference problem under domain shift, assessing whether a predictive function estimated in the training data can maintain stable performance across different ancestries, environments, or technical platforms (Ruan et al., 2021). This stage corresponds to the “PRS → prediction” step and represents the primary point where cross-population failure occurs.

The standard workflow includes independent quality control and allele alignment for external datasets, selection of appropriate LD reference panels based on principal component analysis or ancestry inference, and computation of PRS on a consistent scale. Performance evaluation should then be conducted independently in the external dataset, including discrimination, calibration, and utility assessment, while documenting differences in phenotype definitions and measurement error (Kachuri et al., 2024). Numerous studies have shown that PRS trained in European populations typically experience a 40-60% reduction in predictive accuracy when applied to non-European populations. Multi-ancestry training or methods (e.g., PRS-CSx, CT-SLEB) can partially recover performance, in some cases reaching approximately 80% or more of the source population performance (Duncan et al., 2019; Jung et al., 2025).

From a statistical perspective, this performance decay can be understood as an estimand mismatch caused by differences in LD structure, allele frequency spectra, and effect size distributions across populations. To disentangle structural differences from environmental effects, it is recommended to design multiple external validation datasets (e.g., across ancestries, locations, or years) and perform systematic sensitivity analyses, such as replacing LD reference panels or excluding high-LD regions (Wang et al., 2023).

In addition, cross-population applications must account for data heterogeneity, including inconsistencies in phenotype definitions, missing environmental records, and platform-specific batch effects, all of which may amplify extrapolation error. Therefore, external validation design should incorporate standardized data processing, multidimensional data recording, and cross-platform harmonization to improve interpretability and reproducibility.

2.3 Performance Evaluation Metrics

The effectiveness of PRS/PGS models should be assessed using a multi-dimensional framework that captures predictive accuracy, calibration, and practical decision value. For binary outcomes (e.g., disease status), the area under the receiver operating characteristic curve (AUC) is a primary measure of discrimination (Lennon et al., 2024). For continuous traits, the proportion of variance explained (R^2) and correlation coefficients (r) reflect predictive accuracy, and can be transformed to the liability scale (R^2_liability) for cross-population comparability (Sima et al., 2024).

In terms of effect size, odds ratios (OR) or hazard ratios (HR) per standard deviation of PRS are commonly reported in clinical studies (Patel et al., 2023). Cross-population performance can be quantified using the transferability ratio $T = R^2_{target}/R^2_{source}$ and differences in AUC (Duncan et al., 2019). From a statistical interpretation perspective, R^2 reflects variance explained by genetic signals, whereas AUC reflects the model's ability to rank individuals, corresponding to "variance explanation" and "predictive discrimination," respectively.

At the application level, threshold selection should be guided by decision context. In medical studies, decision curve analysis (DCA) can be used to determine clinically meaningful thresholds based on disease prevalence and intervention costs. For example, OR ≈ 1.5 with good calibration may support enhanced risk screening, whereas OR ≥ 2.0 may justify early intervention for high-risk individuals (Jung et al., 2025). In crop breeding, threshold optimization should consider heritability, environmental heterogeneity, and economic weights, and can be informed by simulations or multi-environment trial data.

To avoid over-reliance on single metrics, it is recommended to report uncertainty intervals, sensitivity analyses, and calibration curves, thereby providing a more robust and comprehensive evaluation of model performance.

3 Joint Prediction of PRS with Environmental and Lifestyle Factors

Within the framework of statistical genetics, PRS fundamentally captures an individual's baseline genetic risk under given genetic information. However, in real-world systems, phenotypes are jointly determined by genetic effects and environmental exposures. Therefore, jointly modeling PRS with environmental or lifestyle factors can be interpreted as a conditional extension of the predictive functional, in which environmental dependence is introduced on top of genetic main effects, thereby improving both predictive accuracy and decision utility.

3.1 Modeling gene-environment interaction (G×E)

In multi-environment trials (METs) or longitudinal population studies, gene-environment interaction (G×E) determines the stability and transferability of predictive functions across different environmental conditions. By using PRS/PGS as a low-dimensional representation of genetic main effects and incorporating environmental variables (e.g., site, year, climate, or lifestyle exposures), a reaction norm framework can be constructed:

$$y_{ij} = \mu + \beta_g \cdot PGS_i + \beta_e \cdot E_j + \beta_{ge} \cdot (PGS_i \cdot E_j) + g_i + (gE)_{ij} + \varepsilon_{ij}$$

where g_i and $(gE)_{ij}$ denote random genetic effects and their interaction with the environment, respectively. These can be modeled using factor-analytic (FA) or kernel-based covariance structures to capture cross-environment correlations. In high-dimensional environmental settings, dimensionality reduction techniques such as principal component analysis or ecological indices are typically applied to distinguish general adaptability from specific adaptability.

In human studies, environmental exposures are often time-dependent (e.g., smoking, diet, physical activity), and can be modeled using logistic regression or survival analysis:

$$h(t \mid PGS, E(t)) = h_0(t)\exp\left(\beta_g \cdot PGS + \beta_e \cdot E(t) + \beta_{ge} \cdot PGS \cdot E(t)\right)$$

Within a statistical modeling framework, the incorporation of G×E effects extend the predictive function from one that depends solely on genetic information to one that is explicitly conditioned on environmental context. In this setting, PRS no longer represents a marginal genetic effect averaged across environments; rather, it acts as a modifier of environmental effects, allowing the relationship between environmental exposure and phenotype to vary systematically across different levels of genetic risk. From this perspective, gene-environment interaction can be understood as heterogeneity in environmental response patterns across strata of polygenic scores, whereby the functional form of the environment-phenotype relationship becomes dependent on PRS. Consequently, prediction shifts from a marginal formulation to a conditional, context-dependent representation (Figure 2).

However, this process is susceptible to multiple sources of bias, including measurement error in environmental variables, time misalignment, and confounding induced by gene-environment correlation (rGE). Therefore, stratified analyses, instrumental variable approaches, or negative control designs are recommended, along with replication in independent cohorts to ensure robustness of interaction effects (Kachuri et al., 2024; Sima et al., 2024).

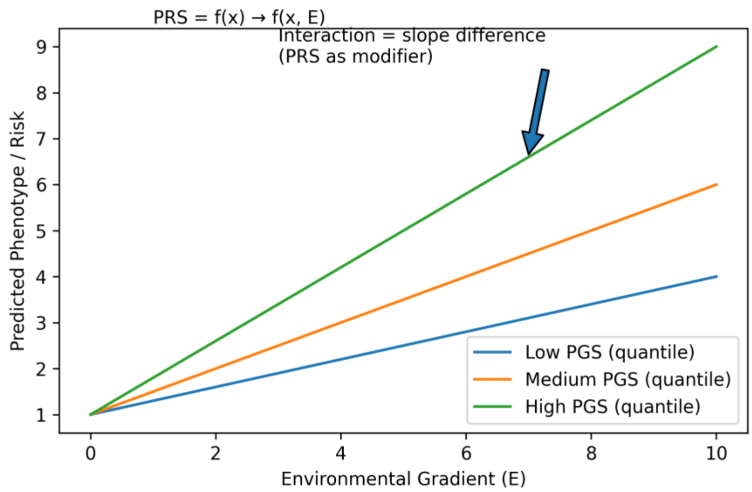

Figure 2 Conditional prediction under gene-environment interaction (G×E): PRS as a function modifier

Note: Illustration of gene-environment interaction (G×E) as differences in slopes across environmental gradients. Each line represents a quantile of polygenic scores (PGS), showing that the effect of environmental exposure on phenotype depends on genetic background. This reflects a conditional predictive function, where PRS modifies the relationship between environment and outcome (PRS = f(x) → f(x, E)).

3.2 Statistical and machine learning models

Within traditional statistical frameworks, joint models are typically formulated as linear or generalized linear models incorporating genetic, environmental, and interaction effects:

$$\eta = \alpha + \beta_g \cdot PGS + \beta_e^{\top} E + \gamma^{\top}(PGS \circ E) + C^{\top}\theta$$

where C represents covariates such as age, sex, ancestry principal components, and batch effects.

In high-dimensional settings, to prevent overfitting, regularization methods such as ridge regression, elastic net, or group lasso are commonly used to impose hierarchical shrinkage on interaction terms, balancing model complexity and predictive stability. In MET designs, leave-group-out cross-validation (e.g., by site or year) should be employed to prevent environmental information leakage.

For time-varying exposures, piecewise time-varying coefficient models or joint longitudinal-survival models can be used to mitigate bias arising from temporal misalignment (Kachuri et al., 2024).

Machine learning methods provide complementary tools for capturing nonlinearities and higher-order interactions. Random forests and gradient boosting machines (GBM) are robust to data heterogeneity and missingness, while deep learning models are suitable for integrating multi-source phenotypic data (e.g., high-throughput phenotyping or wearable device data). However, from a statistical inference perspective, increased model flexibility often comes at the cost of higher estimation bias and greater uncertainty in generalization. Therefore, nested cross-validation, class imbalance reweighting, and post hoc calibration (e.g., Platt scaling or isotonic regression) are essential to control overfitting (Sima et al., 2024).

For model interpretability, SHAP values or permutation importance can be used to quantify the marginal contributions of PRS, key environmental variables, and their interactions. Stability selection across different ancestries or ecological populations can further help identify predictors with consistent effects.

3.3 Predictive gain and decision utility of joint models

The improvement in predictive performance achieved by joint modeling of PRS and environmental factors can be quantified from a variance decomposition perspective:

$$\Delta R^2 = R^2_{\text{joint}} - R^2_G$$

where R^2_G, R^2_E, and R^2_{GE} represent the contributions of genetic main effects, environmental main effects, and interaction effects, respectively, and ΔR^2 reflects the incremental gain of the joint model over PRS alone.

The magnitude of this gain depends on the variability of environmental factors and the strength of G×E interactions. When environmental exposures are modifiable and widely distributed in the target population, joint models often produce steeper risk gradients in the high-risk tail, thereby increasing net benefit in decision curve analysis (Kachuri et al., 2024; Sima et al., 2024).

In population-based studies, the evaluation of PRS is more appropriately conducted within a comparative modeling framework rather than relying on a single model specification. A baseline model incorporating key covariates, such as age, sex, and ancestry principal components, is typically used as a reference, upon which PRS, environmental exposures, and their interaction terms are incorporated. Model performance can then be assessed in a multidimensional manner, capturing both discrimination and explanatory capacity, using metrics such as AUC, R^2 (or liability-scale R^2), effect sizes per standard deviation of PRS (e.g., OR or HR), and net benefit derived from decision curve analysis. Furthermore, stratifying individuals according to lifestyle or environmental exposure levels allows for a more nuanced characterization of risk distributions and calibration patterns, thereby facilitating the evaluation of the "risk equivalence" phenomenon-namely, the extent to which adverse environmental exposures may attenuate or offset the protective effects associated with lower genetic risk (Sima et al., 2024).

In crop breeding, a two-stage decision framework can be implemented: early-generation selection using PGS to improve selection accuracy (correlation r), followed by estimation of environment-specific interaction effects (β_{ge}) in small samples from target environments. This enables a strategy of "general adaptability selection + environment-specific optimization," with theoretical genetic gain expressed as:

$$\Delta G \approx i \cdot r \cdot \sigma_A$$

where i denotes selection intensity and σ_A the additive genetic standard deviation (Ruan et al., 2021). This framework demonstrates that integrating PRS with environmental information not only improves predictive accuracy but also translates directly into higher selection efficiency and practical utility.

4 Ethical and Population Fairness Issues

In the practical application of polygenic risk scores (PRS/PGS), ethical and population fairness concerns arise not only from social structural differences but are also deeply rooted in differences in the applicability of statistical models across populations. From a statistical genetics perspective, cross-population inequity can be understood as inconsistency in the statistical target (estimand) represented by the predictive function across different data domains, leading to systematic performance bias and decision risk.

4.1 Inequity in cross-population prediction

A large body of evidence indicates that PRS/PGS trained predominantly on European populations exhibit substantially reduced predictive performance in non-European populations (approximately 40-80% decline). This reduction is primarily driven by differences in allele frequency spectra and linkage disequilibrium (LD) structure, sampling bias in GWAS discovery and effect estimation, and inconsistencies in phenotype definition and measurement. These factors collectively result in decreased explanatory power, calibration bias, and unstable decision thresholds during extrapolation, thereby increasing misclassification risk and leading to inequitable allocation of resources (Duncan et al., 2019; Martin et al., 2019; Zhang et al., 2023).

From a statistical inference perspective, this phenomenon can be understood as arising from systematic differences across populations in linkage disequilibrium structure, allele frequency spectra, and effect size distributions, which lead to a misalignment between the estimand defined in the training data and the target of prediction in the external population-commonly referred to as estimand mismatch.

Among different populations, individuals of African ancestry and admixed populations are particularly affected, largely due to their higher genetic diversity and the relative lack of representative LD reference panels and functional annotation resources. As a result, tag SNPs are less able to reliably proxy underlying causal variants (Ding et al., 2023; Kachuri et al., 2024).

Similar issues are observed in crop breeding systems. Differences in subspecies structure, ecological population stratification, and the target population of environments (TPE) can lead to failure of PGS models trained on elite germplasm or specific environments when applied to local varieties or marginal ecological conditions. Gene-environment interactions (G×E) further amplify these discrepancies, reducing selection efficiency under environmental extrapolation and potentially leading to systematic neglect of important genetic signals relevant to smallholder farming systems or marginal environments, thereby creating forms of “hidden inequity” (Sima et al., 2024).

4.2 Ethical and societal considerations

Overinterpretation of PRS as a deterministic measure of an individual’s “genetic destiny” may lead to distorted risk perception, stigmatization, and reinforcement of social stereotypes. When predictive performance and decision thresholds are not comparable across populations, the direct application of PRS in screening or intervention may result in unequal distribution of healthcare resources, thereby exacerbating existing health disparities (Martin et al., 2019; Lewis and Green, 2021; Andreoli et al., 2024). In addition, issues related to data governance and privacy are critical, including risks of re-identification, policies for returning results to participants, and mechanisms for dynamic informed consent. These considerations require the integration of ethical evaluation throughout the entire research and implementation lifecycle (Adeyemo et al., 2021). In sensitive domains such as psychiatric traits, particular caution is needed in interpretation and communication to avoid reinforcing genetic determinism or misleading the public (Murray et al., 2020; Chapman, 2022).

In agricultural and breeding contexts, ethical challenges are more closely associated with structural imbalances in technology deployment. For example, recommendations based solely on large-scale data from a single environment may disadvantage niche ecological systems or smallholder farmers, and may, over time, reduce genetic diversity and compromise the resilience of food systems (Sima et al., 2024). Furthermore, access to and utilization of international germplasm resources and genomic data are often highly unequal. Without appropriate frameworks for intellectual property and benefit-sharing, such imbalances may exacerbate global disparities between developed and developing regions. Differences in farmers’ access to data and technology further constrain the equitable implementation of PRS/PGS in real-world agricultural systems.

4.3 Mitigation strategies: a multi-layer framework from data to governance

Addressing inequity in cross-population PRS/PGS applications requires systematic improvements at three levels: data, methodology, and governance.

At the data level, efforts should focus on expanding multi-ancestry and multi-ecological GWAS datasets and reference panels to improve coverage of low-frequency and structural variants, as well as developing comprehensive functional annotation resources across tissues and environments. Standardization of data quality control (QC), genomic coordinates, and allele coding conventions is essential to reduce technical heterogeneity across studies (Zhang et al., 2023; Kachuri et al., 2024; Kullo, 2024). In addition, promoting cross-institutional data sharing and establishing standardized consortia, along with dynamically updated public resource repositories, will improve both representativeness and accessibility of data.

At the methodological level, advances are needed in multi-ancestry joint modeling, hierarchical modeling, ancestry-aware LD modeling, and transfer learning approaches (e.g., PRS-CSx, CT-SLEB, Joint-Lassosum). Incorporating local ancestry information and domain adaptation techniques can further enhance model adaptability to population structure differences. Small-sample reweighting or recalibration in the target population has been shown to effectively reduce performance gaps in practice (Zhang et al., 2023; Kachuri et al., 2024). Furthermore, integrating functional annotations and causal inference approaches as biologically informed priors can reduce noise and improve robustness in cross-population prediction.

At the evaluation and governance level, it is essential to establish a systematic "fairness metric framework," reporting performance metrics separately across populations, including AUC, R^2, calibration slope and intercept, Brier score, net benefit, and reclassification metrics (NRI). Performance differences should be quantified using measures such as the transferability ratio (T) and ΔAUC. In addition, decision thresholds and rules should be optimized for each population, and uncertainty measures (e.g., confidence intervals and calibration curves) should be reported to avoid overinterpretation of single metrics. Adoption of transparent reporting standards (e.g., Polygenic Score Catalog, PRS Reporting Statement) and regulatory and ethical compliance frameworks (Wand et al., 2020; Lewis et al., 2024; Xiang et al., 2024) will further ensure that PRS/PGS applications are scientifically robust, interpretable, and equitable.

5 Discussion

From a unified statistical inference framework, the performance differences among existing PRS/PGS methods fundamentally arise from distinct modeling assumptions regarding effect size distributions, linkage disequilibrium (LD) structure, and sparsity, thereby corresponding to different statistical targets (estimands). From this perspective, methodological evolution can be viewed as a progressive approximation to the question of how GWAS-derived effects can be transformed into stable predictive functions.

Compared with baseline approaches such as clumping and thresholding (C+T), LD-aware Bayesian shrinkage methods (e.g., LDpred2 and PRS-CS) apply continuous shrinkage to effect sizes under LD constraints, typically achieving higher predictive performance and smoother behavior with respect to hyperparameters under the same training data and reference panels. When functional annotations are incorporated (e.g., LDpred-funct and AnnoPred), differential shrinkage or preferential inclusion of variants in functionally enriched regions can further improve the signal-to-noise ratio and partially mitigate cross-population bias induced by tagging effects (Sima et al., 2024). In settings involving heterogeneous data or extrapolation, multi-ancestry and cross-population approaches (e.g., PRS-CSx, hierarchical modeling, and model stacking) balance shared and population-specific effects, often achieving a better trade-off between transferability and stability (Zhang et al., 2023).

Based on these insights, a practical three-step decision framework can be adopted, centered on "scenario-resource-validation." First, modeling strategies should be selected based on the sample size and representativeness of the target population (population-specific models versus multi-ancestry transfer models). Second, method selection should consider the availability of LD reference panels and functional annotations (annotation-informed Bayesian methods versus LD-aware baseline approaches). Third, model selection should be driven by external validation, comparing relative R^2/AUC, calibration slope, and decision-curve net benefit in held-out or independent datasets, with the final model applied only after being frozen (Kachuri et al., 2024).

At the data and modeling levels, future improvements in PRS performance require both expanded data coverage and advances in statistical methodology. On the one hand, efforts should focus on increasing the representation of multi-ancestry GWAS and LD reference panels, improving the capture of low-frequency and structural variants, and implementing standardized quality control across centers and platforms in human studies, as well as covering the target population of environments (TPE) through multi-environment trials (METs) in crop systems (Wang et al., 2018). On the other hand, modeling strategies should incorporate ancestry-aware LD structures, hierarchical random effects, and transfer learning approaches to decompose shared and population-specific effects. In target populations, recalibration (e.g., slope and intercept adjustment) and reweighting (stacking) can reduce predictive bias, while the integration of local ancestry and functional annotations can further improve cross-population robustness (Cai et al., 2021; Zhang et al., 2023).

At the evaluation level, a shift from single performance metrics to a systematic assessment framework is needed. In addition to reporting R^2 and AUC, studies should report the transferability ratio ($T = R^2_{target}/R^2_{source}$), population-stratified calibration metrics (slope and intercept), and decision-curve net benefit. Sensitivity analyses with respect to LD reference panels, functional annotation strength, and model parameters should also be conducted, forming a closed-loop evaluation framework of “training-extrapolation-recalibration-re-evaluation.”

At the application level, PRS/PGS are evolving from predictive tools toward decision-support systems. In medicine, combining PGS with age, family history, biomarkers, and lifestyle factors enables stratified screening and personalized interventions for high-burden diseases such as cardiovascular, metabolic, and certain cancers. In crop breeding, PGS is methodologically aligned with genomic selection (GS), and can be used for early-stage preselection and multi-environment reaction norm modeling to achieve coordinated optimization of “general adaptability and environment-specific selection,” thereby substantially improving genetic gain per unit time in complex stress-related traits (Wang et al., 2018; Alemu et al., 2024).

Despite these advances, several key bottlenecks remain. First, imbalances in multi-ancestry data and functional annotation resources lead to training bias and uncertainty in evaluation. Second, low-frequency and rare variants, as well as structural variants (e.g., SVs and CNVs), are not fully captured under current “tag SNP” frameworks, requiring advances in pangenome references, long-read sequencing, and multi-omics data integration for improved causal inference. Third, cross-platform batch effects and residual population structure may further amplify extrapolation errors (Du et al., 2025). From an ethical and governance perspective, medical applications must address risks of genetic determinism and discrimination, and establish frameworks for dynamic consent and data sovereignty; in breeding, considerations of biodiversity conservation, equitable benefit sharing, and support for smallholder systems are essential to avoid structural bias driven by performance optimization alone (Gorjanc et al., 2017; Broesch et al., 2020).

Looking forward, the development of PRS/PGS can be summarized within an integrated paradigm: multi-ancestry data expansion + causal and functional annotation integration + ancestry-aware modeling + environment coupling + recalibration and fairness evaluation

This paradigm will facilitate the transition of PRS/PGS from standalone predictive tools to comprehensive platforms that are transferable, interpretable, and governable.

6 Conclusion

Polygenic risk scores (PRS/PGS) systematically integrate GWAS-derived effect estimates to transform locus-trait associations into actionable individual-level predictive measures. In both human medicine and crop breeding, they support risk stratification, early screening, and selection decisions, serving as a key bridge between fundamental genetics and translational applications.

From a statistical genetics perspective, PRS is not merely a predictive tool but a model-dependent predictive function, whose performance and scope are jointly determined by training data, LD structure, and effect estimation methods. In correspondence with SNP heritability as a measure of variance explained, PRS represents the expression of genetic signal at the individual prediction level. Together, they form a variance-prediction duality. Within this framework, the decline in cross-population predictive performance can be understood as an estimand mismatch arising from differences in LD structure, allele frequency spectra, and effect distributions across populations.

At present, cross-population robustness remains the central bottleneck for translating PRS/PGS into clinical and agricultural practice. Advances in multi-ancestry data resources and methodology are progressively addressing this challenge. Multi-ancestry training, hierarchical modeling, ancestry-aware LD modeling, and the integration of local ancestry information enable improved balance between shared and population-specific effects. The incorporation of functional annotation and causal refinement further reduces the impact of tagging effects on cross-population prediction. At the application level, adherence to a standardized workflow-“training-validation-freezing-external evaluation” -together with multi-dimensional performance metrics for predictive accuracy and fairness, is increasingly recognized as best practice.

Looking forward, the development of PRS/PGS is expected to follow three major directions. First, integration of causal inference and functional annotation will enhance signal identification and cross-population robustness through structured priors. Second, multi-ancestry modeling and transfer learning will reduce performance gaps in underrepresented populations. Third, coupling with environmental and lifestyle factors will extend predictive functions into context-dependent models through explicit modeling of gene-environment interaction. In medicine, these advances will support stratified screening and personalized interventions for high-burden diseases; in crop breeding, they will enable efficient strategies combining general adaptability with environment-specific optimization.

At the same time, several key challenges remain. These include imbalances in multi-ancestry data and annotation resources, limited coverage of low-frequency and structural variants, cross-platform batch effects, and residual population structure, as well as ethical and governance considerations such as data sovereignty and fairness. With the development of pangenome reference systems, long-read sequencing, and multi-omics integration, along with the establishment of open benchmarks, standardized quality control, and transparent reporting frameworks, PRS/PGS are expected to evolve into a general predictive platform that is scientifically robust and socially responsible, with broad applications in global health and food security.

Author Contributions

Xuanjun Fang conducted the study, including literature review, data analysis, and drafting and revising the manuscript. The author has read and approved the final version of the manuscript.

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Review Article Open Access

Agronomic Characteristics and Production Application Evaluation of the Early-Maturing and High-Yield Conventional Indica Rice Variety Zhongzu 100

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Abstract Zhongzu 100 is a newly approved conventional early indica rice cultivar jointly developed by Longyou Wuguxiang Seed Industry Co., Ltd. and the China National Rice Research Institute. This study systematically evaluates its breeding background, agronomic characteristics, grain quality traits, stress resistance performance, and production application value based on official variety registration data, regional trial results, production trials, and relevant literature. The results indicate that Zhongzu 100 possesses a moderate growth duration, compact plant architecture, synchronized maturity, favorable population uniformity, and stable yield performance. In Zhejiang provincial regional trials, the variety achieved a yield advantage over the control cultivar and demonstrated strong adaptability to early-rice production systems. Grain quality evaluation showed acceptable milling and edible quality, although further improvement in appearance quality remains desirable. Disease resistance assessment revealed moderate susceptibility to rice blast and relatively weak resistance to bacterial leaf blight, indicating the need for appropriate disease management during cultivation. Case studies further confirmed its suitability for large-scale production, mechanized cultivation, and commercial seed promotion. Overall, Zhongzu 100 represents a practical and productive early-rice cultivar that successfully balances earliness, yield potential, and production stability. The variety has considerable significance for improving early-rice productivity, supporting regional agricultural development, and promoting innovation within the seed industry. Future efforts should focus on enhancing grain quality, strengthening disease resistance, and expanding regional adaptability evaluation.

Keywords Zhongzu 100; Early indica rice; Agronomic characteristics; Production application; Varietal evaluation

1 Introduction

Rice remains one of the clearest links between agronomy and food security. It is still the staple food for more than half of the global population, is cultivated in more than one hundred countries, and depends heavily on Asian production systems. Those broad facts matter for this paper because they explain why variety improvement in rice is rarely just a technical matter of plant type or grain shape. In practice, every new cultivar is judged by whether it can fit real farming schedules, maintain supply, and keep enough market acceptability to be worth planting at scale. For China, where rice remains central to food supply, varietal progress in major production regions has long carried weight far beyond the field itself (Fukagawa and Ziska, 2019).

Within China, early rice plays a special role in the southern and central rice belt where double-cropping systems remain agronomically and economically important. In these systems, the value of an early variety is not defined by yield alone. It must vacate the field on time, leave a workable window for the following crop, and mature uniformly enough to reduce losses and labor friction. That is why early-maturing cultivars are often asked to carry several goals at once: moderate duration, sufficient tillering, decent grain filling, acceptable cooking quality, and enough stability to perform under humid and disease-prone environments. The difficulty of breeding such a combination explains why many useful early-rice cultivars are not “perfect” in every trait, but instead become successful because they solve the practical bottlenecks of a specific production system (Peng et al., 2009; Li et al., 2017).

The continuing demand for improved early-rice cultivars also needs to be understood in the context of modern Chinese breeding. Since the rise of hybrid rice and later the broader super-rice program, the national discussion has often emphasized high yield. Yet farmers and seed enterprises still need dependable conventional varieties, especially where seed saving, seed multiplication, production timing, and local adaptation remain central. In that sense, conventional early indica rice still has a practical place in modern seed systems. It offers breeders a pathway to combine yield stability with reproducibility, and it offers farmers a cultivar type that can be integrated into local management more predictably than some intensive, narrowly adapted materials (Wang, 2015; Varshney et al., 2019).

Zhongzu 100 emerged from exactly this practical breeding environment. According to the company dossier, the variety was jointly developed by Longyou Wuguxiang Seed Industry Co., Ltd. and the China National Rice Research Institute, approved in Zhejiang under the number Zheshendao 2020003, and bred from the cross Zhongzao 25/Zhe 1345. The same dossier states that the variety was recognized as a Super Rice variety in 2025 and that the company has established a stable seed base with distribution extending beyond Zhejiang to Jiangxi, Fujian, Anhui, and Guangxi. Those details matter not just as background but because they define the current evidence base: most publicly traceable agronomic and application data still come from variety-registration tests and enterprise-linked demonstration materials, not from a large body of independent peer-reviewed field studies focused specifically on Zhongzu 100. The purpose of this study is therefore straightforward. Rather than treating Zhongzu 100 as an abstract genotype or inflating it into a universally superior cultivar, this paper evaluates what the currently available evidence actually supports. It asks four practical questions. First, what agronomic features define Zhongzu 100 as an early indica variety? Second, how strong are its quality and resistance profiles in real breeding terms? Third, where does its production value lie in Zhejiang-style early-rice systems? Fourth, what are the limits of the current evidence, and what directions would make the variety more useful in future breeding and commercialization? The discussion that follows is built around those questions, using the official dossier as the factual core and the published literature as the interpretive frame.

2 Breeding Background and Origin of Zhongzu 100

2.1 Current status of early indica rice breeding in China

The breeding of early indica rice in China has entered a stage where simple earliness is no longer enough. Historically, early-ripening rice was valued because it made multiple cropping possible and reduced the risk of missing the second season. That logic still holds. But today’s breeding targets are broader. Early rice must now be early without becoming too light-yielding, compact without sacrificing panicle productivity, and reasonably acceptable in quality without losing field robustness. In other words, breeders are no longer choosing between duration and productivity as sharply as before; they are expected to deliver both, while also paying attention to plant uniformity and practical cultivation needs. This is especially true in regions where labor constraints, disease pressure, and a push toward mechanization have changed what farmers expect from a successful early-rice variety (Peng et al., 2009; Nie and Peng, 2017).

Another important feature of the current breeding landscape is that early indica rice is not being improved in isolation. It is developed within cropping systems. In Zhejiang and other southern rice regions, the real value of earliness lies in whether the variety creates breathing room for the next crop, particularly in double-cropping arrangements. This makes maturity synchronization, harvest appearance, and post-harvest field turnover as relevant as plot yield. A cultivar that matures a few days earlier, stands more evenly, and colors better at harvest may offer advantages that are not fully captured by simple yield rankings. That is one reason why many productive modern early-rice cultivars are assessed not only by grain output but also by whether they move smoothly through the field calendar (Li et al., 2017; Zhang et al., 2021).

The same trend also explains why the improvement of conventional early indica rice still matters in the era of hybrid rice. Hybrid rice has contributed enormously to food security, but conventional varieties continue to fill important roles in regional adaptation, seed production, and management flexibility. For seed enterprises and farmers alike, a conventional variety with a stable phenotype and manageable disease risks may be more useful than a theoretically superior cultivar that is difficult to multiply or fit into the local production rhythm. Zhongzu 100 belongs to that practical category. Its breeding significance lies less in radical novelty and more in the attempt to balance traits that early-rice farmers actually need (Wang, 2015).

2.2 Breeding institutions and scientific basis of Zhongzu 100

The institutional background of Zhongzu 100 is worth noting because it reflects a well-established but still highly relevant model in Chinese crop improvement: collaboration between a research institute with breeding capacity and a local seed enterprise with multiplication and extension strength. The company dossier identifies the applicants and breeders as Longyou Wuguxiang Seed Industry Co., Ltd. and the China National Rice Research Institute, with named breeders including Zhan Yousong, Ji Zhijuan, Yang Changdeng, Zeng Yuxiang, and Liang Yan. This pairing gives the variety a distinctly applied character. It was not generated in a purely academic breeding program detached from commercialization, nor was it only an enterprise selection effort without scientific backing. It sits in the middle, where breeding, registration, multiplication, and promotion can be linked more directly (Figure 1).

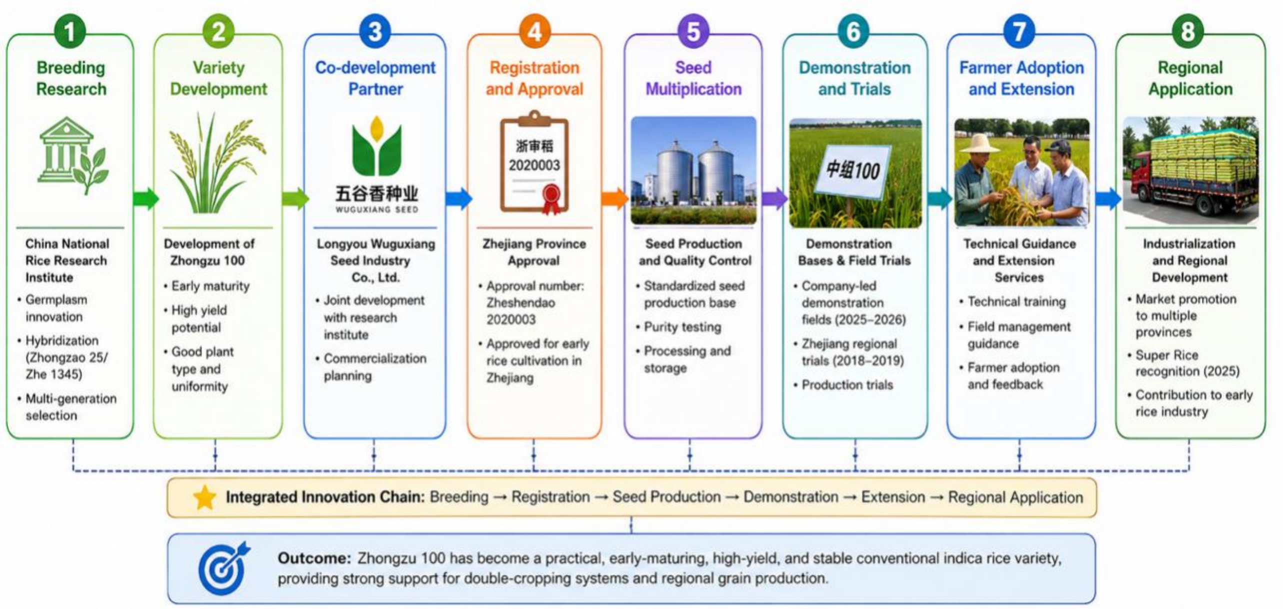

Figure 1 Breeding, registration, and extension pathway of Zhongzu 100

Scientifically, the dossier makes clear that Zhongzu 100 was derived through conventional hybridization and selection, not transgenic or genome-editing approaches. That point matters for how the variety should be positioned. In a journal such as *Genomics and Applied Biology*, the word “genomics” can tempt authors to overstate molecular depth even when the available evidence does not warrant it. In the case of Zhongzu 100, the sounder description is simpler: this is a conventionally bred early indica variety whose value comes from trait integration as demonstrated in provincial testing and practical seed-industry use. The scientific basis is therefore classical breeding-parental recombination, multi-stage selection, and official agronomic validation-rather than a genomics-heavy pedigree dissection (Chen et al., 2019).

This public–private cooperation model also has wider significance. In seed-industry terms, a variety becomes influential not only when it is agronomically good, but when the institutions behind it can produce enough seed, maintain quality control, and organize effective extension. The company dossier emphasizes that Wuguxiang has a stable seed-production base, storage and processing infrastructure, standard testing facilities, and sales channels extending to multiple provinces. That does not prove the variety is universally superior, but it does mean Zhongzu 100 entered the market with a stronger commercialization platform than many good varieties that remain trapped at the registration stage.

2.3 Parentage and breeding process of Zhongzu 100

The official dossier records the pedigree of Zhongzu 100 as Zhongzao 25/Zhe 1345. This is the one fully traceable parentage statement currently available in the supplied materials, and it should be treated as the starting point for any discussion of breeding origin. What the dossier does not provide is a detailed breakdown of the parental traits or the generation-by-generation selection process. That gap is important. It means the paper can accurately describe the cross and institutional origin, but it should not pretend to know exactly which component of the final phenotype came from which parent, or claim a molecular explanation that has not been documented in the available source.

Even so, some modest inferences are reasonable. Because the variety was ultimately approved as a conventional early indica rice with a short growth duration, relatively short stature, stronger tillering, and decent grain filling, the breeders were almost certainly selecting toward a practical combination of earliness and production stability rather than toward premium grain quality alone. The resulting trait package supports that interpretation. Zhongzu 100 does not look like a quality-specialty cultivar. It looks like a production-oriented early-rice line shaped by the demands of provincial testing and field promotion. That kind of selection logic is consistent with the broader orientation of applied rice breeding in southern China, where the target is often a workable balance rather than a single highly optimized trait (Peng et al., 2009).

The breeding process should therefore be framed carefully in publication writing. A defensible description would be that Zhongzu 100 was developed through conventional crossing and selection, then evaluated through Zhejiang provincial early-indica regional and production trials, after which it entered seed multiplication and demonstration through a company-led extension system. What cannot be responsibly stated, because the current materials do not show it, is any detailed marker-assisted selection scheme, genomic selection pipeline, or parent-specific trait decomposition. Restraint here is not a weakness; it is exactly what keeps the manuscript aligned with academic integrity.

2.4 Variety approval and promotion history of Zhongzu 100

The approval history of Zhongzu 100 is one of the strongest parts of its documentary record. The official approval number given in the company dossier is Zheshendao 2020003, and the variety is identified as suitable for early-rice planting in Zhejiang Province. This is not a trivial point. Provincial approval means the variety has moved beyond internal selection and has already been tested against at least one recognized local benchmark, in this case Zhongzao 39. The approval opinion is also quite specific: Zhongzu 100 is described as a mid-maturing conventional early indica rice with neat and uniform field growth, comparatively short plants, luxuriant growth, stronger tillering, green-stem yellow-ripening behavior in the later stage, good color conversion, and good yield potential, while also being moderately susceptible to blast and highly susceptible to bacterial leaf blight.

Promotion history is more unevenly documented, but still meaningful. The dossier states that the company maintains a stable seed base and that seed is sold not only within Zhejiang but also into Jiangxi, Fujian, Anhui, and Guangxi. It also reports that in 2025 Zhongzu 100 was recognized as a Super Rice variety by the Ministry of Agriculture and Rural Affairs. Because that recognition was not independently verified from an official government database during this review, the most accurate wording is to say that it is reported in the company dossier. Even with that caveat, the reported sequence-provincial approval, seed-base construction, interprovincial marketing, and super-rice recognition-suggests a cultivar that has moved from local testing into a more visible commercialization stage.

This sequence also hints at how Zhongzu 100 should be understood at present. It is not yet a heavily studied “model variety” in the literature. Instead, it is a recently promoted production cultivar whose public profile is being built through registration data, company extension, and market circulation. That status shapes the rest of this paper. The evidence for Zhongzu 100 is strongest when discussing agronomic registration traits and actual production performance in Zhejiang; it is weaker when making broader claims about long-term national adaptation or disease durability across many rice ecologies. A credible evaluation has to keep that difference in view.

3 Major Agronomic Characteristics of Zhongzu 100

The core agronomic profile of Zhongzu 100 is summarized in Table 1. Because the current evidence base is still concentrated in official registration and company materials, the table intentionally presents only traceable indicators rather than speculative traits.

Table 1 Major agronomic characteristics and yield-related performance of Zhongzu 100

Trait category	Official indicator for Zhongzu 100	Practical interpretation
Approval number	Zheshendao 2020003	Approved for Zhejiang early-rice cultivation
Growth duration	111.7 days	Slightly earlier than the control; useful for field turnover
Comparison with control	1 day shorter than Zhongzao 39	Modest but practical earliness
Plant height	86.5 cm	Shorter plant type, generally favorable for standability
Effective panicles	212,000 per mu	Reflects relatively strong tillering and panicle formation
Total grains per panicle	126.4	Moderate panicle size
Filled grains per panicle	108.2	Indicates good grain filling
Seed-setting rate	85.7%	One of the main contributors to yield stability
Thousand-grain weight	26.3 g	Medium grain weight for production-oriented early rice
Regional-trial yield	567.9 kg/mu average	Equivalent to about 8.52 t/ha
Production-trial yield	558.8 kg/mu	Equivalent to about 8.38 t/ha
Milling quality	52.9% head milled rice	Acceptable but not elite
Blast resistance	Leaf blast 2.9; panicle blast 8; index 5.1	Moderate susceptibility overall, with panicle blast concern
BLB resistance	7.1	High susceptibility to bacterial leaf blight

Note: Hectare equivalents were calculated as yield (kg/mu) × 15 ÷ 1000. Source: compiled from the official variety dossier and trial materials

3.1 Growth duration and maturity characteristics

Maturity is the first trait that gives Zhongzu 100 its production identity. In the two-year Zhejiang provincial regional trials, the average whole growth duration was 111.7 days, which was one day shorter than the control variety Zhongzao 39. On paper, one day may look minor. In practice, however, timing in early-rice systems is often decided at the margins. A cultivar does not need to be dramatically earlier to be useful; it only needs to ripen early enough, consistently enough, to relieve pressure on harvest scheduling and the transition to the next crop. That is particularly true in double-cropping contexts, where delayed harvest of the first season can compress the management window of the second (Li et al., 2017).

The approval opinion classifies Zhongzu 100 as a mid-maturing conventional early indica rice. That wording deserves attention. It implies the variety is not an extremely ultrashort type, which can sometimes sacrifice biomass accumulation or sink capacity, but a moderate-duration early cultivar that still keeps the field calendar favorable. This middle position may be part of its practical attraction. In early-rice breeding, extremely short duration can create its own problems, including lower biomass, weaker panicle size, or narrower adaptation. Zhongzu 100 instead appears to occupy a more balanced maturity class-early enough for production needs, but long enough to support stable panicle formation and grain filling (Peng et al., 2009).

The company dossier also notes good color conversion and a later-stage “green stem, yellow maturity” appearance. This harvest phenotype is not just cosmetic. In production terms, a variety that ripens more evenly and shows a clearer transition toward harvest maturity is easier to judge in the field and less likely to create confusion about cutting time. For early rice, where the farm calendar can be tight, synchronized maturity can save labor and reduce the risk of mixed-moisture harvesting. Zhongzu 100’s maturity value therefore lies not only in raw days-to-harvest, but in the more complete package of field timing and harvest readiness.

3.2 Plant morphology and population structure

Zhongzu 100 is described in the official dossier as a relatively short-statured plant with erect flag leaves, green foliage, and a medium panicle type. It is also awnless, with yellow lemma tips and culms. The average plant height in provincial testing was 86.5 cm. This stature is agronomically meaningful. In early-rice systems, a shorter plant type often supports better standability and more manageable canopy structure, especially under fertilization regimes that could otherwise push vegetative growth too far. A medium-height, compact canopy does not guarantee lodging resistance on its own, but it generally gives breeders and farmers a better starting point than a tall, top-heavy phenotype (Islam et al., 2007).

The erect flag-leaf character is also useful to note. Erect upper leaves can improve canopy light distribution and are frequently associated with more efficient source–sink relationships in modern rice ideotypes. Again, this should not be overstated. The dossier does not provide physiological measurements such as leaf angle dynamics, chlorophyll persistence, or radiation-use efficiency. But from a field agronomy perspective, erect leaves combined with shorter plants and a medium panicle type often point toward a practical, well-organized population structure rather than an overly luxuriant, shading canopy. That matters for early rice, where humid field conditions can intensify disease and where uniform stand architecture helps field management (Peng et al., 2009).

The approval opinion further emphasizes that Zhongzu 100 grows neatly and uniformly in the field. This point may sound routine, but it is not. Population uniformity is one of the most undervalued agronomic traits in variety evaluation because it affects everything from disease scouting to fertilizer response to harvest timing. A field population that matures unevenly can look acceptable in plot statistics while performing poorly in real farm operations. Zhongzu 100 appears to avoid that problem. Its morphological value, then, is not rooted in a single striking organ trait, but in a coherent plant type that supports orderly field performance.

3.3 Tillering ability and panicle characteristics

One of the clearest strengths of Zhongzu 100 is its tillering capacity. The official materials repeatedly describe its tillering ability as relatively strong, and the two-year regional trials recorded an average of 212,000 effective panicles per mu. For early rice, this is an important trait because strong but productive tillering helps compensate for the shorter vegetative period compared with longer-duration rice types. A variety that can rapidly establish enough effective panicles without turning excessively leafy often gains an advantage under time-constrained double-cropping conditions.

The panicle itself is described as medium in size, with an average of 126.4 total grains per panicle and 108.2 filled grains. These numbers suggest that Zhongzu 100 does not depend on very large panicles to achieve its yield level. Instead, its structure seems to rely on a combination of moderately sized panicles and a relatively high number of effective panicles per area. From a crop-architecture standpoint, this is often a safer yield strategy than pursuing oversized panicles in early rice, since extremely large panicles may not fill well under rapid seasonal development or variable early-season weather (Peng et al., 2009).

The awnless character further improves the practical impression of the panicle type. Awnless grains generally facilitate harvest, threshing, seed handling, and post-harvest processing. They also make the harvested material look cleaner and more standardized in seed-production settings. While this is not a dramatic scientific breakthrough, it is exactly the kind of trait that matters when a cultivar is expected to move beyond small experimental plots into commercial seed multiplication and farm-scale production. Zhongzu 100's tillering and panicle phenotype therefore fits its larger identity as a production cultivar rather than a narrowly specialized line.

3.4 Yield components analysis

The yield of Zhongzu 100 is best understood as the result of balance rather than extremity. Its effective panicle number is substantial, its panicle size is moderate, its filled grain number is high relative to total grain number, and its seed-setting rate reaches 85.7%. The thousand-grain weight is 26.3 g, which is solid but not unusually large. When these elements are viewed together, the architecture of yield becomes clear: Zhongzu 100 is not winning through massive grain size or giant panicles alone. It is performing through a coordinated set of moderate-to-good component traits, especially panicle number and grain filling.

That balance is important because yield components in rice often compensate for one another. More panicles can come at the expense of panicle size; larger panicles can dilute grain filling; heavier grains may not appear if sink size outruns source strength. Zhongzu 100 seems to avoid strong imbalance. Its seed-setting rate is particularly notable in this context. An average of 108.2 filled grains out of 126.4 total grains per panicle implies that sink production is being matched by a reasonably efficient reproductive outcome. For a practical early-rice cultivar, that is often more valuable than a higher maximum grain number that does not translate into filled grain (Peng et al., 2009; Calingacion et al., 2014).

For readers more used to hectare-based international reporting, the conversion of registered yields also helps put Zhongzu 100 into perspective. The two-year average regional-trial yield of 567.9 kg per mu is equivalent to roughly 8.52 t/ha, and the production-trial yield of 558.8 kg per mu is about 8.38 t/ha. These are respectable values for an early conventional indica cultivar in a provincial evaluation context. They do not justify any exaggerated "record-breaking" description, but they do support the view that Zhongzu 100 is a genuinely high-yielding type within its agronomic class.

3.5 Evaluation of high-yield and stable-yield performance

The most reliable official yield evidence for Zhongzu 100 comes from the Zhejiang early-indica regional and production trials. In 2018, the variety yielded 577.1 kg per mu, 3.3% higher than Zhongzao 39, but the gain did not reach statistical significance. In 2019, it yielded 558.7 kg per mu, 4.0% above the same control, again without significance. Across the two years, the average was 567.9 kg per mu, 3.7% above Zhongzao 39. In the 2019 production trial, the mean yield reached 558.8 kg per mu, 8.3% higher than the control. These numbers tell a nuanced story: the registration data support a real and consistent yield advantage, but they do not support careless claims of dramatic superiority in all comparisons.

This nuance is precisely why Zhongzu 100 should be described as a stable-yielding rather than sensational variety. In breeding and extension, non-significant but repeated yield advantages still matter, especially when they are accompanied by good field order, maturity fit, and practical seed-industry support. The stronger increase observed in the production trial is also instructive. Production trials often better reflect more realistic cultivation conditions and broader management packages. The larger gain there suggests that Zhongzu 100 may express its value more clearly under practical production than under the stricter variance of regional testing alone. That interpretation should remain cautious, but it is reasonable (Peng et al., 2009).

In short, Zhongzu 100's high-yield identity is credible, but its credibility depends on honest wording. It is not a miracle cultivar that overwhelms the control by enormous margins. It is a productive early-rice variety with a repeatable mean advantage, a balanced yield-component structure, and a phenotype that seems suited to orderly field production. For growers and seed companies, that may be more useful than a more volatile high-peak type. Stability, after all, is often what converts a good candidate into a sellable variety.

4 Grain Quality Characteristics and Stress Resistance Performance of Zhongzu 100

4.1 Milling quality characteristics

According to the official rice quality tests conducted in 2018–2019 in Hangzhou, Zhongzu 100 had an average head milled rice rate of 52.9%. This figure places the variety in a workable but not outstanding category from a post-harvest processing perspective. Milling quality matters because it influences both market return and processing efficiency. Even a productive field variety can lose value if too much grain is broken or downgraded in milling. In that sense, the recorded milling performance of Zhongzu 100 supports its role as a usable production cultivar, but it does not place it in the top tier of premium-milling rice types (Custodio et al., 2019).

This is consistent with the broader identity of the variety. Everything in the dossier suggests that Zhongzu 100 was bred mainly for agronomic practicality rather than premium niche quality. That is not a criticism. In many early-rice production systems, especially where the primary goal is timely output and cropping continuity, acceptable milling quality is enough. A variety does not need elite quality to be valuable if it performs well in the field, fits the seasonal window, and produces grain that can move reliably through normal processing channels. Zhongzu 100 appears to meet that standard, even if it is not designed as a processing-quality flagship (Fitzgerald et al., 2009).

4.2 Appearance quality and eating quality

The appearance-quality profile of Zhongzu 100 is more mixed. Official testing recorded a length-to-width ratio of 2.4, a chalky grain rate of 65.5%, chalkiness of 11.4%, transparency of grade 3.5, gel consistency of 56 mm, and amylose content of 25.3%. The two-year comprehensive assessment placed the variety in the general edible-rice category under the Chinese ministerial standard. This is a very important conclusion and should be reported plainly. Zhongzu 100 is not best presented as a high-end eating-quality rice; it is better described as a practical early-rice variety with general consumer quality.

Among these indicators, chalkiness is the clearest weakness in appearance quality. Chalky kernels often reduce visual appeal and can negatively affect market preference, especially in more quality-sensitive retail segments. The amylose content, on the other hand, suggests a relatively typical non-sticky indica eating profile, and the gel consistency does not indicate an excessively hard-cooking grain. In other words, the eating quality may be acceptable for everyday use even if the appearance quality is not especially refined. This distinction matters because practical varietal value often depends on whether a rice type is acceptable in ordinary channels, not whether it wins a premium-quality competition (Champagne et al., 2010; Custodio et al., 2019).

For publication purposes, the fairest summary is that Zhongzu 100 offers serviceable grain quality aligned with general edible use, while leaving clear space for improvement in appearance-related traits. That conclusion actually strengthens the paper's credibility. A manuscript that admits a variety's quality limits while still explaining its agronomic value reads as more trustworthy than one that tries to make every trait sound exceptional. In the case of Zhongzu 100, quality is adequate but not elite, and that should be viewed as one of the main targets for future breeding refinement (Alam et al., 2024).

4.3 Resistance to rice blast

Rice blast remains one of the most serious diseases of rice globally and is especially important in humid environments where the disease can damage leaves, nodes, and panicles. The disease is notorious not simply because it infects rice, but because panicle and neck infection can directly damage reproductive success and grain filling. For breeding and cultivation alike, blast resistance therefore has to be judged across growth stages, not only at the leaf stage (Wilson and Talbot, 2009; Dean et al., 2012).

In Zhongzu 100, the official resistance profile is clearly uneven. The average leaf blast score was 2.9, which is not alarming on its own. But the panicle blast score reached 8, the panicle blast loss rate score was 4, and the comprehensive blast index was 5.1. On that basis, the approval opinion describes the variety as moderately susceptible to rice blast. This is a sensible and measured classification. It means Zhongzu 100 should not be rejected outright in blast-prone regions, but it also should not be promoted as though blast management were a marginal issue. In practical terms, the concern is less the leaf-stage score and more the clear vulnerability at the panicle stage.

This distinction matters because panicle blast can sharply reduce the effective conversion of reproductive sinks into harvestable grain, even when vegetative growth looks strong. Zhongzu 100's relatively good grain-filling profile in registration trials suggests that disease pressure was manageable under the test conditions, but that does not eliminate the risk of yield instability when the disease is severe. The dossier therefore gives a concise but important cultivation recommendation: timely control of rice blast. That single sentence is one of the most agronomically consequential lines in the entire document, and any realistic production evaluation of Zhongzu 100 has to take it seriously (Liu and Zhang, 2022).

4.4 Resistance to bacterial leaf blight

If blast is a significant management concern in Zhongzu 100, bacterial leaf blight is an even clearer weakness. Official testing recorded a bacterial leaf blight score of 7.1, and the approval opinion classified the variety as highly susceptible. Unlike some varietal descriptions that soften disease limitations behind vague wording, the Zhongzu 100 dossier is quite direct here. That clarity is helpful. It leaves no room for presenting the cultivar as broadly disease resistant when the evidence says otherwise.

Bacterial leaf blight is a destructive rice disease with the potential to reduce both yield and grain quality, especially when infection develops early and favorable weather supports rapid spread. Modern resistance breeding has made considerable progress, including the use of resistance genes such as Xa4, xa5, xa13, Xa21, Xa33, and

Xa38, and even genome-editing approaches targeting SWEET-related susceptibility pathways. The fact that Zhongzu 100 remains highly susceptible suggests that resistance to this disease was not a major strength selected into the released line, or at least not a strength maintained strongly enough in the final phenotype (Oliva et al., 2019; Varshney et al., 2019).

From a production standpoint, this matters in three ways. First, it limits the ecological breadth at which the variety can be promoted with confidence. Second, it raises the management threshold for growers in humid, blight-prone regions. Third, it narrows the room for low-input cultivation, since disease risk may demand more careful monitoring and intervention. For a practical early-rice cultivar, high susceptibility does not erase all value, but it does redefine where and how that value can be realized. Zhongzu 100 should therefore be described as agronomically promising but pathologically incomplete-a productivity-oriented line that still needs stronger disease protection in future improvement work (Nino-Liu et al., 2006).

4.5 Comprehensive evaluation of stress resistance

When grain quality and disease resistance are considered together, Zhongzu 100 emerges as a typical example of a useful but not all-around variety. Its strengths are clear: orderly plant type, moderate earliness, solid yield components, and repeatable production performance. Its weaknesses are equally clear: grain quality is only general rather than premium, and disease resistance-especially to bacterial leaf blight-is not strong. This pattern is not unusual in practical breeding. Many varieties reach the field not because they are flawless, but because they solve the most urgent production problem of a particular region more effectively than the alternatives (Peng et al., 2009).

In Zhongzu 100, the main production problem being addressed appears to be the need for an early conventional indica rice that yields well, matures neatly, and can be multiplied and extended reliably through an established seed enterprise. That orientation helps explain why the variety was still commercially advanced despite its resistance limitations. In other words, its stress-resistance profile does not make it unsuitable; it simply means that its deployment requires management awareness. The variety is best suited to farmers and extension systems that can match timely cultivation with timely disease control.

A balanced academic evaluation should therefore avoid two extremes. It should not dismiss Zhongzu 100 because it lacks premium quality or broad disease resistance, and it should not overpraise it as though those deficiencies did not matter. The more accurate conclusion is that Zhongzu 100 is a production-effective early-rice cultivar with a clear agronomic identity and equally clear breeding room for improvement. That position-useful, promotable, but still improvable-is precisely what makes it worth discussing in a review-style paper (Custodio et al., 2019; Varshney et al., 2019).

5 Analysis of Production Application Advantages of Zhongzu 100

5.1 Significance of early maturity in double-cropping rice systems

In double-cropping rice regions, maturity is not an isolated trait. It is a scheduling tool. A variety that matures on time helps create space for land preparation, residue management, and the timely establishment of the following crop. This is why even modest reductions in growth duration can have meaningful value in production systems, especially under unstable weather or labor shortages. Early maturity also reduces the chance that the first crop will collide with the seasonal requirements of the second crop, which is one of the oldest and still most practical reasons why fast-ripening rice remains agronomically important in East and Southeast Asia (Peng et al., 2009; Li et al., 2017).

Zhongzu 100 fits this logic well. Its 111.7-day growth duration and one-day advantage over the control do not make it an ultra-short variety, but they do support a smoother seasonal transition. The approval description of good color conversion and orderly maturity strengthens this point. In practice, the value of an early-rice cultivar is not just how soon it can theoretically be cut, but how uniformly and predictably the stand reaches harvest readiness. Zhongzu 100 appears to offer exactly that kind of “usable earliness,” which may be more meaningful for farmers than a nominally shorter duration with unequal ripening.

A further advantage of moderate earliness is risk distribution. When the first crop leaves the field on schedule, farmers retain more flexibility for the second season and more room to respond to weather variation. In humid southern systems, that flexibility can influence not only yield but also management cost and harvest loss. For that reason, Zhongzu 100's maturity should be treated as one of its central production assets, not a side note attached to yield evaluation (Zhang et al., 2021).

5.2 Contribution of high and stable yield to grain production

Yield remains the trait most likely to determine whether a variety is widely adopted, and Zhongzu 100 performs well enough in official trials to deserve attention on that front. Its repeated advantage over Zhongzao 39 across two regional-trial years, combined with the larger gain in the production trial, suggests that the cultivar offers not only productive potential but also a certain degree of consistency. In real grain production, that combination is often more valuable than occasional high peaks followed by weak seasons.

This is especially relevant for a conventional early-rice variety. Because early rice is sometimes viewed as the less profitable or more compressed season within double-cropping systems, a cultivar that can sustain respectable yield without creating major management complications helps preserve the viability of the whole cropping structure. Zhongzu 100's yield profile indicates that it can function as a dependable first-season crop rather than merely a necessary placeholder before late rice. That matters for regional food supply and for farm-level economics alike (Peng et al., 2009; Muthayya et al., 2014).

The wording "high and stable yield" is therefore appropriate for Zhongzu 100 if used carefully. "High" is supported by the absolute and comparative trial figures. "Stable" is supported by the fact that yield advantage persisted across two years and showed stronger expression again in the production trial. What is not supported is any claim that the variety is universally superior in all ecological conditions. Its contribution is better understood as regionally useful, system-compatible productivity.

5.3 Agronomic characteristics favorable for mechanized cultivation

Mechanization is increasingly shaping how rice varieties are judged, even when explicit machine-harvest trials are not available. Farmers and seed enterprises want cultivars that stand evenly, mature synchronously, avoid excessive height, and produce grain that can be harvested and processed with minimal field loss. Zhongzu 100 was not accompanied in the dossier by dedicated mechanization test data, so any evaluation here must remain inferential. Even so, the recorded agronomic traits do point in a favorable direction.

Several characteristics support this inference. The plant height is relatively low at 86.5 cm. The flag leaves are erect. The panicle type is medium. The crop is awnless. The approval opinion emphasizes neat field growth and good maturity coloration. Taken together, these are exactly the kinds of traits that usually make field operation smoother, especially when harvest timing depends on a narrow window or when uniformity matters for machine entry. None of this proves superior machine performance by itself, but it strongly suggests that Zhongzu 100 was not bred with a morphology that resists mechanized adoption (Islam et al., 2007).This matters commercially because production extension today often succeeds where agronomic convenience and business convenience meet. A variety that is easier to multiply, easier to manage, and easier to harvest has more room to spread through seed networks. Zhongzu 100's field phenotype appears to support that kind of scaling. The more precise conclusion, however, is that the variety is mechanization-friendly in trait profile, while still needing direct machine-harvest evaluation for stronger scientific confirmation. That distinction should be preserved in publication writing.

5.4 Advantages in field uniformity and synchronous maturity

Uniformity can be easy to overlook because it is less dramatic than yield figures, but in practice it is one of the most farmer-relevant traits a variety can have. Zhongzu 100 was officially described as having neat and consistent field growth, luxuriant vigor, stronger tillering, later-stage green stems with yellow maturity, and good color conversion. This paints a picture of a crop population that develops in a coordinated way rather than in a strongly variable one. For practical cultivation, that matters at every stage: fertilizer timing, disease observation, irrigation management, and harvest scheduling all become easier when plants move together.

Synchronous maturity also reduces one of the subtle losses in rice production: decision uncertainty. When a field contains too many plants at different maturity stages, harvest timing becomes a compromise and some portion of the stand is almost always cut either slightly early or slightly late. That can affect grain moisture, appearance, milling quality, and even seed production quality. Zhongzu 100's uniformity therefore strengthens its identity not only as a grain cultivar but also as a seed-industry cultivar, because seed multiplication relies heavily on phenotypic consistency and timely harvest (Kumar and Kalita, 2017).

There is also a psychological side to uniformity. Farmers often trust a variety more when it "looks right" in the field-clean, even, and predictable. This may sound anecdotal, but adoption often depends on visual confidence as much as on formal statistics. Zhongzu 100's published descriptors suggest it performs well in that respect, which likely contributes to its extension value beyond the numerical trial record alone.

5.5 Adaptability in Zhejiang Province and surrounding regions

At present, the strongest direct evidence for Zhongzu 100's adaptability comes from Zhejiang. It completed two years of provincial regional testing and one production trial there, and it was approved specifically for early-rice planting in the province. That is enough to support a solid claim of Zhejiang adaptation. It is not enough to claim equally strong adaptation across all southern rice ecologies. This distinction may seem obvious, but it matters greatly in academic writing, where a variety's known adaptation zone should not be casually expanded beyond the actual evidence.

The dossier does, however, report seed marketing to Jiangxi, Fujian, Anhui, and Guangxi. Commercial circulation into these provinces suggests that Zhongzu 100 is already being treated as a cultivar with broader promise, especially in ecologies that share some overlap with Zhejiang's early-rice systems. That implication is reasonable, but it remains an extension signal rather than a fully documented scientific conclusion. More multi-location data would still be needed to make a stronger adaptation claim in publication.

For now, the most accurate evaluation is that Zhongzu 100 has demonstrated proven adaptability in Zhejiang and plausible extension potential in neighboring and comparable provinces. That is already meaningful. Many varieties fail to generate even that much confidence. Zhongzu 100 appears to have crossed the threshold from local candidate to regional option, but it has not yet accumulated enough public comparative evidence to be described as broadly validated across all double-cropping areas of southern China.

6 Case Studies of Production Application of Zhongzu 100

The case evidence for Zhongzu 100 is important not because it replaces formal trials, but because it shows how official varietal performance translates into seed-industry practice. In the current stage of the variety's development, review writing is strongest when it combines the official agronomic record with the documented setting of company-led seed production and demonstration rather than pretending there is already a large independent application literature on this cultivar.

6.1 Application case at the demonstration base of Longyou Wuguxiang Seed Industry Co., Ltd.

The materials supplied for this study document a demonstration and seed-production base linked to Longyou Wuguxiang Seed Industry Co., Ltd., the enterprise that co-developed and applied for Zhongzu 100 (Figure 2). The company profile describes established office, storage, processing, and testing facilities, together with a stable seed-production base and a full chain from production to sales. In practical terms, that means Zhongzu 100 is not being promoted as an isolated experimental line. It is embedded in a seed-enterprise system capable of multiplication, processing, and extension. That institutional setting is itself a case of production application, because many new varieties fail not in breeding but in the transition from breeding to scalable dissemination.

The field and facility photographs supplied with the dossier reinforce this point visually. They show a formal seed-enterprise environment rather than an ad hoc demonstration setting, and they include a labeled Zhongzu 100 field plot. When considered alongside the company's reported infrastructure and seed-base capacity, these materials support the interpretation that enterprise-led demonstration has been one of the main channels through which Zhongzu 100 moved toward wider application. The significance of this is not simply promotional. Enterprise demonstration can accelerate adoption because it links cultivar identity, seed purity, technical guidance, and market supply in one operating system.

Figure 2 Longyou Wuguxiang Seed Industry Co., Ltd. facilities and Zhongzu 100 field demonstration plot (Photoed by Geyang Zhan)

As a case, this base also illustrates a broader pattern in contemporary seed extension. Farmers often adopt new varieties more quickly when they can observe a clean, uniform, manageable stand under local conditions and when the seed source appears credible and organized. Zhongzu 100's documented demonstration environment therefore strengthens its application profile, even though the supplied materials do not provide detailed replicated on-farm comparison data from the base itself. The case is valuable precisely because it shows how enterprise organization can shorten the distance between breeding output and production uptake.

6.2 Regional and production trial case in Zhejiang Province

Among all application-related evidence, the Zhejiang trial results remain the most solidly documented. In the provincial early-indica regional trials, Zhongzu 100 yielded 577.1 kg per mu in 2018 and 558.7 kg per mu in 2019, with increases of 3.3% and 4.0% over Zhongzao 39, respectively. Across the two years, the mean was 567.9 kg per mu, 3.7% higher than the control. In the 2019 production trial, the average yield was 558.8 kg per mu, 8.3% above the control. These numbers provide the clearest formal case that Zhongzu 100 has both regional adaptability and practical yield potential in Zhejiang early-rice conditions.

The meaning of this case is broader than one set of percentages. Regional trials test whether a candidate variety can repeatedly perform under the ecological and management diversity represented in the official testing network. Production trials then move one step closer to the field reality of extension. Zhongzu 100 performed credibly in both contexts. The yield advantage in the production trial, being larger than the two-year regional-trial mean, suggests that the variety may fit routine cultivation relatively well. Although such an interpretation should remain cautious without raw variance data, it is still one of the strongest arguments for the cultivar's practical applicability (Peng et al., 2009).

This case also clarifies why Zhongzu 100 should be discussed as a production-oriented variety. It was not approved on the basis of extraordinary quality traits or broad-spectrum resistance. It was approved because it offered a coherent field package that translated into a repeatable yield advantage in the target province. For a variety intended for real extension, that is not a secondary outcome; it is the central one. Zhejiang trial performance, therefore, remains the anchor case for any serious evaluation of Zhongzu 100.

6.3 Promotion case following super rice recognition

The third application case concerns visibility and market expansion after reported Super Rice recognition. According to the company dossier, Zhongzu 100 was recognized as a Super Rice variety in 2025 by the Ministry of Agriculture and Rural Affairs, and the same dossier notes that the company already had stable production bases and marketing channels extending to several provinces. Because the super-rice recognition was not independently retrieved from a government database in this review, the correct academic phrasing is that the recognition is reported in the supplied dossier. Even with that caution, the production implication is straightforward: such recognition can raise a variety's market profile and make further extension easier.

In China's rice sector, the term "super rice" carries symbolic as well as technical weight. It signals that a variety has entered a higher-visibility category associated with strong yield-oriented breeding. For a local seed enterprise, this can make a substantial difference. Recognition helps with branding, increases confidence among distributors and growers, and can make demonstration activities more persuasive. In that sense, the reported super-rice status of Zhongzu 100 may have accelerated commercialization even if the variety's actual agronomic strengths remained the same as those already visible in provincial testing (Wang, 2015).

The larger lesson of this case is that variety dissemination depends on institutional signals as much as on field data. A good cultivar becomes easier to promote when it is backed by approval, demonstration, recognizable institutional partnerships, and policy-linked labels. Zhongzu 100 seems to have benefited from all of these. That does not make it automatically superior in every environment, but it does explain why the variety appears to be moving from a purely provincial testing identity into a broader commercial one.

7 Challenges and Future Development Directions for Zhongzu 100

7.1 Disease management requirements in production

The most immediate production challenge for Zhongzu 100 is disease management. Moderate susceptibility to rice blast and high susceptibility to bacterial leaf blight mean that the variety cannot be treated as a "low-maintenance" line in all environments. In humid rice systems, disease pressure can quickly erase part of the yield advantage of an otherwise promising cultivar. The official recommendation to control rice blast in a timely manner is therefore not a routine note; it is a necessary condition for stable performance (Wilson and Talbot, 2009).

This challenge is especially important for enterprise-led expansion. Once a variety moves beyond its original testing province, disease patterns may shift, and susceptibility can become more costly if extension messages are simplified into "high yield" without enough management detail. For Zhongzu 100, responsible promotion should therefore include location-specific disease guidance rather than seed sales alone. That is a practical point, but also a scientific one, because varietal performance is always the product of genotype and management together.

Future development could proceed in two ways. One is agronomic: better disease forecasting, timely sprays, and management packages adapted to local risk. The other is breeding: introducing stronger resistance, especially to bacterial leaf blight, into the Zhongzu 100 genetic background or into a next-generation derivative. Given the pace of modern resistance breeding, including genomics-assisted selection and genome-edited resistance strategies in other rice backgrounds, this is a realistic rather than speculative target (Varshney et al., 2019; Oliva et al., 2019).

7.2 Potential for further grain quality improvement

A second challenge lies in grain quality. Zhongzu 100 is acceptable for general edible use, but the official results leave no doubt that it is not a premium-quality variety, especially with respect to appearance. High chalky grain rate and notable chalkiness reduce visual appeal and may limit market competitiveness where consumer preference is shifting toward cleaner, more refined grain presentation. In many rice markets, quality no longer sits behind yield as a secondary issue; it increasingly shapes whether a cultivar can move from basic production into higher-value circulation (Custodio et al., 2019; Alam et al., 2024).

For Zhongzu 100, that means yield-oriented success does not eliminate the need for quality-oriented breeding. If the variety is to strengthen its long-term market position, future improvement should aim to preserve the current maturity and yield balance while reducing chalkiness and, if possible, enhancing milling recovery and eating quality consistency. That is not a simple task, since quality and early maturity can be difficult to optimize together. But it is the most obvious route if breeders want to move the variety family beyond a strictly “production practical” role (Fitzgerald et al., 2009; Sreenivasulu et al., 2015).

The point is not that Zhongzu 100 has failed in quality terms. It has not. Rather, it has reached a useful but ordinary level. In breeding language, that often means the line has already proven its agronomic value and is ready for a second round of refinement aimed at the market. For varietal development, that is a normal and productive stage to be in.

7.3 Need for broader regional adaptability evaluation

The third major challenge is evidentiary breadth. Zhongzu 100 has convincing provincial data from Zhejiang and supportive application signals from company-led extension, but publicly available multi-location evidence across the full range of its marketed provinces is still limited in the materials reviewed here. This does not invalidate the variety’s promise. It simply means that claims of wide regional adaptability should remain measured until stronger comparative data from Jiangxi, Fujian, Anhui, Guangxi, and other relevant ecologies are assembled.

This matters scientifically because early-rice performance is highly sensitive to ecology. Differences in temperature accumulation, disease pressure, soil fertility, transplanting time, and harvest season humidity can change how a cultivar expresses yield, maturity, and grain quality. A variety that performs neatly in Zhejiang may still need adjustment or may even reveal hidden weaknesses elsewhere. Broader testing, therefore, is not only a commercial formality. It is the next necessary step in defining the true adaptation envelope of Zhongzu 100 (Peng et al., 2009; Li et al., 2017).

One useful future direction would be multi-year, multi-site evaluation that combines agronomic yield traits with disease scores, grain quality, maturity synchronization, and basic mechanization observations. That would allow Zhongzu 100 to be judged not merely as a registered cultivar in one province, but as a regional seed product with a more transparent ecological profile. Without that step, commercialization may still progress, but the scientific characterization of the variety will remain incomplete.

7.4 Optimization of supporting cultivation techniques

No variety performs independently of cultivation technique, and this is especially true for early rice. The official dossier of Zhongzu 100 offers only one brief technical point-timely prevention and control of rice blast. That recommendation is important, but it also signals a broader gap: the publicly available materials do not yet provide a full agronomic package for seedling age, transplanting density, fertilization timing, water management, or harvest strategy. For publication purposes, it is better to acknowledge this directly than to fill the gap with generic cultivation advice presented as variety-specific evidence.

This missing package matters because a balanced cultivar like Zhongzu 100 is likely to respond well to appropriately tuned management. Its yield depends on preserving effective panicle number, maintaining grain filling, and preventing disease damage during reproductive stages. That suggests that supporting techniques should focus on steady stand establishment, moderate vegetative balance, and careful disease surveillance rather than excessive nitrogen-driven growth. But until formal variety-specific technical recommendations are published, these remain agronomic inferences rather than documented prescriptions (Peng et al., 2009).

Future work should therefore treat cultivation optimization as part of the variety’s development rather than an afterthought. In modern seed extension, a variety plus a reliable management package is often more valuable than a better variety presented without one. For Zhongzu 100, supporting techniques may ultimately determine whether its registered agronomic advantages are fully realized in ordinary farmer fields.

7.5 Future trends in variety improvement and industrial development

Looking ahead, the future development of Zhongzu 100 likely depends on whether breeders and seed enterprises can keep its current strengths while correcting its obvious weaknesses. The strengths are already visible: moderate earliness, a compact and orderly plant type, useful yield stability, and commercialization through a functioning seed enterprise. The weaknesses are equally visible: susceptibility to major diseases and a grain-quality profile that is practical but not refined. The next-generation development path is therefore fairly clear-even if the exact breeding route is not yet documented in the current materials.

In breeding terms, there are three likely directions. One is resistance upgrading, especially against bacterial leaf blight. Another is appearance-quality improvement without losing field performance. The third is broader ecological validation so that commercialization is matched by stronger scientific characterization. These are not isolated goals. In modern rice breeding, their interaction matters as much as each trait itself. A variety that improves disease resistance but loses maturity fit may not be a better production tool. Conversely, a line that refines quality but becomes less stable in early-rice systems may lose its regional value (Chen et al., 2019; Varshney et al., 2019).

On the industrial side, Zhongzu 100 also exemplifies a likely trend in regional seed development: closer coupling of breeding, enterprise multiplication, demonstration, and market branding. If this model continues, the most successful cultivars may not be those with the single best trait, but those that can travel most smoothly through the full chain from selection to farmer adoption. Zhongzu 100 already shows part of that pathway. Whether it becomes more influential will depend on how effectively its next stage combines trait improvement with industrial organization.

8 Value of Zhongzu 100 in Modern Seed Industry Development

8.1 Significance for national food security

The contribution of a variety like Zhongzu 100 to food security is not dramatic in the way record-yield cultivars sometimes are. Its significance is quieter and, in many ways, more practical. It offers a productive conventional early-rice option for a system where the first season still matters for total annual grain output and for the continuity of double-cropping schedules. In food-security terms, reliable earlier-season supply can be just as important as very high peak yields in one segment of the calendar. That is especially true in a country where rice remains a central staple and where varietal diversification itself is part of production resilience (Fukagawa and Ziska, 2019).

There is also strategic value in maintaining strong conventional rice breeding alongside more celebrated hybrid or high-tech pathways. A seed system that depends too narrowly on one varietal type becomes more vulnerable. Zhongzu 100 contributes to diversity within the breeding and seed landscape: it widens the menu of early-rice choices and offers a cultivar that combines regional adaptation with enterprise-based seed multiplication. That is a modest but real contribution to grain-security architecture (Wang, 2015).

8.2 Contribution to the upgrading of the early rice industry

The early-rice industry is often pressured by a familiar set of problems: narrower planting windows, labor constraints, relatively modest price premiums, and concern that shorter-season cultivars may compromise quality or yield. Zhongzu 100 addresses part of this by showing that a conventional early indica variety can still deliver a respectable yield package while keeping a growth duration suitable for regional production schedules. Although its grain quality remains only general, its field phenotype and yield stability help make early rice look less like a compromise crop and more like a viable commercial crop in its own right.

From an industry-upgrading perspective, this matters because cultivar choice often determines whether early rice remains attractive enough for continued planting. A practical, orderly, commercially multiplied variety can help stabilize production enthusiasm where the early season might otherwise lose competitiveness. Zhongzu 100 therefore contributes to industry upgrading not by redefining what early rice is, but by making existing early-rice production somewhat easier to sustain and extend (Peng et al., 2009).

8.3 Support for innovation in the seed industry

Zhongzu 100 also has value as a seed-industry case. Its development and promotion show how a local seed enterprise can collaborate with a national research institute, bring a conventional variety through approval, build seed multiplication around it, and then push outward into broader regional markets. That is innovation in an applied sense. It is not innovation because the variety depends on a novel molecular platform; it is innovation because scientific breeding and commercial organization were effectively joined.

This kind of innovation is often underestimated in academic writing, where "innovation" can be reduced too quickly to laboratory technique. But in actual agricultural development, the ability to transform a breeding line into a distributed, reproducible, trusted seed product is itself a form of innovation. The company dossier, with its emphasis on base construction, processing facilities, testing rooms, stable channels, and market expansion, shows that Zhongzu 100 is part of such a system. That is one reason the variety deserves attention beyond its agronomic numbers alone (Kumar and Kalita, 2017).

8.4 Contribution to farmers' income growth

Direct farm-income data for Zhongzu 100 are not included in the current materials, so any statement on income must be framed as a production inference rather than a measured accounting result. Even so, the logic is straightforward. If a variety provides a small but repeatable yield advantage, matures in time for the following crop, and performs uniformly enough to simplify harvest and management, it has the potential to improve farm returns through both output and scheduling efficiency. Zhongzu 100 fits that description reasonably well.

The scheduling dimension is especially important. In double-cropping systems, a first-season variety can contribute to income not only by its own grain yield, but by protecting the timeliness, and therefore profitability, of the second crop. That means the economic value of Zhongzu 100 is probably larger than its single-season yield advantage alone would suggest. However, since the current paper does not have farm-budget or cost-return datasets, the responsible wording is that Zhongzu 100 likely supports income growth through stable productivity and cropping-system coordination, rather than claiming a quantified profit increase (Li et al., 2017).

8.5 Promotion of regional agricultural high-quality development

Regional agricultural development increasingly depends on whether local breeding, seed production, and field extension can reinforce each other. Zhongzu 100 offers a useful example for Zhejiang and surrounding areas because it is tied to a real seed enterprise with visible infrastructure, stable multiplication capacity, and a product already moving beyond its original approval province. In that sense, the variety contributes to high-quality regional development not only as a biological material, but as a node in a broader agricultural service chain.

This contribution should not be exaggerated into a transformational national story. Zhongzu 100 is better understood as a solid regional cultivar whose development pathway reflects the kind of grounded, enterprise-linked seed innovation that high-quality agriculture often depends on. Its story is therefore useful beyond the variety itself. It shows that agricultural upgrading can be built from relatively practical traits-maturity fit, stable yield, field uniformity, reproducible seed supply-when those traits are embedded in functioning local institutions. That is a more realistic picture of high-quality development than the language of "breakthrough" alone.

9 Conclusions and Future Perspectives

9.1 Summary of the major advantages of Zhongzu 100

Zhongzu 100 can be summarized as a practical, production-oriented conventional early indica rice variety whose main advantages lie in balanced agronomic performance rather than in any single extreme trait. It matures slightly earlier than the local control, maintains a relatively short and orderly plant type, produces a strong panicle number, shows good seed setting, and delivers a repeatable yield advantage in Zhejiang official trials. Its field phenotype-uniform growth, good color conversion, and synchronous maturity-adds significant production value that simple yield figures alone do not fully capture.

9.2 Evaluation of current research and application status

The strongest evidence for Zhongzu 100 currently comes from the official variety dossier, Zhejiang regional and production trials, and company-linked demonstration and seed-production materials. This is both a strength and a limitation. It is a strength because the variety's basic agronomic identity is already clearly documented. It is a limitation because broader independent studies, multi-location adaptation analyses, and variety-specific cultivation-package reports are still limited in the public domain. As a result, the present evaluation is strongest when discussing Zhejiang performance and practical seed-industry application, and more cautious when considering broader ecological generalization.

9.3 Future prospects for promotion and application

The future of Zhongzu 100 appears promising if promotion remains matched to realistic management conditions. In Zhejiang and comparable early-rice areas, the variety has clear extension value as a moderate-early, relatively high-yielding, commercially supported cultivar. Its prospects would be strengthened substantially by three developments: broader regional validation, clearer variety-specific cultivation guidance, and continued enterprise-led demonstration that keeps seed purity and technical support aligned. Promotion should emphasize its actual strengths-timing, field order, yield stability-rather than ignoring its disease-management requirements.

9.4 Implications for early rice breeding and production in China

For Chinese early-rice breeding, Zhongzu 100 offers a useful reminder that effective varieties do not need to be flawless to be important. What matters most is whether the trait combination fits the production system. Zhongzu 100 shows that a conventional early indica variety can still be valuable in a modern seed industry if it combines workable earliness, balanced yield components, and strong extension support. At the same time, its limitations point clearly toward the next breeding priorities for early rice in China: stronger resistance to blast and bacterial leaf blight, better appearance quality, and broader adaptation testing carried out alongside real commercialization pathways.

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Effects of Irrigation Frequency on Growth, Fruit Development and Fruit Quality in Melon

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Abstract Melon is a high-value horticultural crop whose market performance depends not only on yield, but also on sweetness, texture, appearance, and storability. Among irrigation variables, frequency is especially important because it controls how often the root zone is rewetted, how strongly soil or substrate moisture fluctuates, and how stable the physiological environment remains during flowering, fruit set, enlargement, and ripening. This review examines how irrigation frequency influences melon growth, fruit development, and fruit quality under open-field, protected, soil-grown, and soilless systems. The literature shows a clear pattern: very infrequent irrigation often restricts leaf expansion, photosynthesis, and fruit growth because melon is sensitive to sudden water deficits, particularly around flowering and early fruit enlargement. By contrast, overly frequent irrigation can sustain vegetative vigor and fruit enlargement but may dilute soluble solids, increase cracking risk in some systems, and reduce water productivity when total water input is excessive. Between these extremes, stage-specific scheduling tends to perform best. Studies from semi-arid and greenhouse systems consistently indicate that adequate or relatively frequent irrigation during flowering and early fruit growth is needed to protect yield, whereas mild deficit or reduced irrigation frequency during late maturation can improve soluble solids, vitamin C, antioxidant activity, firmness, and sometimes reduce cracking without a major yield penalty. Evidence from eastern China, including a two-year greenhouse muskmelon experiment in Haining, Zhejiang, indicates that a moderate irrigation regime can produce a better balance between yield, quality, irrigation water use efficiency, and nitrogen use efficiency than either lower or higher water inputs. In northwestern China and other water-limited regions, pulsed drip irrigation, sensor-guided scheduling, and regulated deficit irrigation have shown strong promise for sustaining fruit quality while reducing water use. Overall, the review argues that irrigation frequency should be treated as a developmental and quality-management tool rather than simply a calendar decision. Future research should separate the effects of frequency from total irrigation amount, compare cultivar-specific responses, and strengthen evidence from humid protected systems such as those common in the Yangtze River Delta.
Keywords Melon; Irrigation frequency; Fruit development; Fruit quality; Deficit irrigation; Drip irrigation; Protected cultivation; Water use efficiency

1 Introduction

Melon is one of the most commercially important fruit vegetables in warm and semi-arid production regions, and it is also widely grown in protected structures where fruit appearance, sweetness, and uniformity determine market value. Recent irrigation research continues to treat melon as a strategic crop because of its high economic return per unit area and its sensitivity to water management. A recent greenhouse-melon study in Taiwan, citing FAOSTAT, described worldwide melon production at roughly 29.48 million tons over more than 1.09 million hectares, while a greenhouse muskmelon study from southeast China emphasized that China remains the dominant producer and that melon occupies a central place in the country's protected horticulture systems. These studies are useful for a review because they connect agronomic management with market quality, not just yield.

Melon also has a distinct position in horticultural research because fruit value is shaped by multiple traits at once. Consumers and supply chains judge melons by soluble solids, sugar-acid balance, firmness, flesh color, aroma, netting or skin appearance, and shelf-life behavior. This means irrigation research on melon rarely ends with a simple "more water versus less water" conclusion. Instead, the key question is how to regulate water in a way that preserves enough vegetative strength to fill fruit while also favoring the quality traits that make fruit saleable. Recent studies on fruit development, sugar metabolism, firmness, and ripening biology reinforce this point by showing that fruit growth and quality formation are tightly linked developmental processes (Cheng et al., 2022; Gustani et al., 2024; Wang et al., 2025).

Water management in melon has become more difficult for two reasons. The first is the broad pressure of water scarcity in many melon-producing regions, including semi-arid Mediterranean zones, northwestern China, and dry parts of North America. The second is that melon quality responds not only to total irrigation amount, but also to the timing and rhythm of water delivery. A global meta-analysis of vegetable deficit irrigation showed that mild to moderate deficit can often preserve yield better than severe deficit, but melon-specific studies make clear that the developmental stage at which the deficit occurs is just as important as the severity itself (Fabeiro et al., 2002; Singh et al., 2021; Yavuz et al., 2021). In protected systems the challenge is even more delicate. Over-irrigation can reduce water use efficiency, increase nutrient leaching, dilute sweetness, and in some cases aggravate fruit cracking, while under-irrigation can suppress canopy development, reduce leaf gas exchange, and limit fruit growth. A two-year commercial melon study in Murcia showed that sensor-guided irrigation reduced water inputs by 27%-30% without yield loss and increased both water and nitrogen productivity, which suggests that a major part of the problem is not lack of technology but lack of precise scheduling. Likewise, a recent greenhouse muskmelon study reported that mild water deficit at fruit maturity significantly lowered cracking while improving commercial quality, showing that “too much” irrigation can be harmful late in the cycle (Zapata-García et al., 2023; Xue et al., 2025).

Irrigation frequency is the temporal dimension of irrigation management. Total seasonal water amount matters, but the interval between irrigation events determines how strongly roots experience drying cycles, how much oxygen remains in the root zone, how stable nutrient transport is, and how sharply the plant alternates between high and low water status. In melon, this matters because fruit growth depends on continuous assimilate supply and sustained cell expansion, while sweetness and firmness often improve when late-season water supply becomes slightly more restrictive. For this reason, frequency should not be treated as a secondary technical detail. It is a direct regulator of source-sink relations, root uptake, and final fruit quality (Sensoy et al., 2007; Li et al., 2012; Sun et al., 2024). The evidence now comes from several kinds of systems. Open-field work has compared longer and shorter irrigation intervals across fixed water amounts. Protected-environment studies have tested pulsed irrigation several times per day, especially in drip and soilless systems. Newer precision-irrigation studies go further by combining irrigation timing with plant-based or sensor-based signals, effectively turning irrigation frequency into a variable that changes with crop stage and crop stress rather than with a fixed calendar. This shift is particularly important for melon because the sensitive phases are not identical from transplanting to ripening (Chang et al., 2019; Zapata-García et al., 2023; Fang et al., 2026).

This study examines irrigation frequency from the perspective of three connected outcomes: vegetative growth, fruit development, and fruit quality. Instead of treating water management as a purely engineering issue, the discussion follows melon development across stages and asks how irrigation rhythm changes canopy formation, root activity, fruit set, fruit enlargement, ripening, and commercial quality traits. It also considers regional case studies, with special attention to eastern China and the Zhejiang-related context, because protected melon production in those regions makes irrigation scheduling especially consequential. The study finally summarizes sustainable strategies, recent technological advances, current research limitations, and practical directions for future work.

2 Water Requirements and Growth Characteristics of Melon

2.1 Growth and development stages of melon

Melon growth is typically divided into an early vegetative stage, a flowering and fruit-set stage, a fruit enlargement stage, and a maturation or ripening stage. Although these labels are simple, the physiological meaning of each stage is different. During early vegetative growth, the plant is building photosynthetic area and root capacity. During flowering and fruit set, reproductive stability becomes critical because water stress can interfere with flower function, fruit initiation, and the early cell division processes that largely determine later fruit size. During enlargement, fruit becomes a dominant sink for water and photoassimilates. During maturation, the balance shifts from rapid accumulation of fresh mass toward sugar concentration, metabolic change, aroma formation, and tissue softening (Fabeiro et al., 2002; Liu et al., 2024; Wang et al., 2025).

Recent developmental studies support this stage-based view. Transcriptomic and metabolomic analyses show that melon fruit follows a strong developmental sequence in which early growth is associated with active cell division and expansion, and later stages are associated with sharp changes in sucrose, organic acids, texture-related pathways, and ripening regulation. A 2025 transcriptome-metabolome study described middle and late fruit development as a typical S-shaped growth process, while a 2024 time-series transcriptome study confirmed clear differences between earlier and later maturity stages in sugar and organic-acid metabolism. This matters for irrigation research because the same water regime cannot be expected to serve all developmental goals equally well (Liu et al., 2024; Wang et al., 2025).

2.2 Water demand during different growth stages

Melon does not demand water uniformly across the season. Early vegetative growth requires enough moisture to support establishment and leaf area development, but seasonal demand often peaks from flowering into fruit enlargement, when transpiration and sink demand are both high. Stage-based deficit irrigation experiments have repeatedly shown that water restriction during blooming or fruit set is more damaging to yield than comparable restriction imposed later. In the classic controlled-deficit study by Fabeiro and colleagues, deficits during blooming most strongly reduced production, deficits during setting affected both quantity and quality, and deficits during ripening had a stronger effect on quality than on yield (Fabeiro et al., 2002).

More recent work confirms that stage sensitivity remains a central principle. Yavuz and colleagues, working in a semi-arid environment, found the highest yields under stress-free irrigation across all stages, but they also showed that different stage combinations shifted quality and water use efficiency in different ways. Kuscu and Turhan later reported that maintaining full irrigation up to fruit ripening and then shifting to 50% ETc produced nearly the same three-year average yield as full irrigation while improving water productivity and several quality traits. In greenhouse substrate production, Xue and colleagues found that mild deficit during maturity reduced cracking and improved quality without a significant penalty in yield. Together these studies suggest that melon water demand is highest, and least negotiable, before and during early fruit growth, while the late stage offers more room for quality-oriented adjustment (Yavuz et al., 2021; Kuscu and Turhan, 2022; Xue et al., 2025).

2.3 Physiological responses of melon to water availability

When water becomes limiting, melon responds through declines in leaf water status, stomatal conductance, transpiration, and net photosynthesis. These are not abstract laboratory traits; they directly shape fruit growth because they determine how much carbon and water are available for sink tissues. Recent studies in field and greenhouse systems show that moderate water deficits can be tolerated if leaf gas exchange remains high enough and if the plant avoids prolonged turgor loss. Under severe or prolonged deficits, however, stomatal closure and reduced photosynthesis lead to smaller canopies, weaker fruit growth, and lower yield (Miceli et al., 2023; Panda et al., 2025; di Santo and Barrios-Masias, 2026).

At the same time, melon does show some capacity for acclimation. In a recent study combining deficit irrigation with biostimulant preconditioning, melon plants under a suppressed-irrigation treatment showed evidence of osmotic adjustment, and the biostimulated treatment further improved water uptake and irrigation water productivity while increasing phenolic compounds in fruit. This is important because it shows that the physiological response to irrigation frequency is not determined by water alone; root-zone conditions, stress history, cultivar traits, and biological inputs can all shift the plant’s response threshold (Zapata-García et al., 2025).

2.4 Critical irrigation periods for melon production

The literature points to two especially critical periods. The first is flowering to early fruit enlargement, when water deficits can reduce fruit set, lower fruit number, and restrict the cell division and early expansion that underpin later fruit size. The second is fruit maturity, not because the plant becomes fragile in the same way, but because water status at this stage strongly affects soluble solids, firmness, cracking risk, and market quality. This second period is therefore critical in a different sense: it is the stage where water can be adjusted most effectively to reshape quality (Fabeiro et al., 2002; Yavuz et al., 2021; Xue et al., 2025).

For growers, the practical implication is straightforward. Irrigation frequency should be higher or at least more stable when the crop is setting and enlarging fruit, especially in protected systems with shallow effective rooting or soilless substrate (Figure 1). Later, once marketable fruit size is largely established, reducing frequency or applying mild deficit can improve sweetness and reduce cracking, provided the stress remains controlled and does not become severe enough to depress yield. That principle appears consistently in studies from Spain, Turkey, Taiwan, and China despite differences in climate and production system (Kuscu and Turhan, 2022; Sun et al., 2024; Xue et al., 2025; Fang et al., 2026).

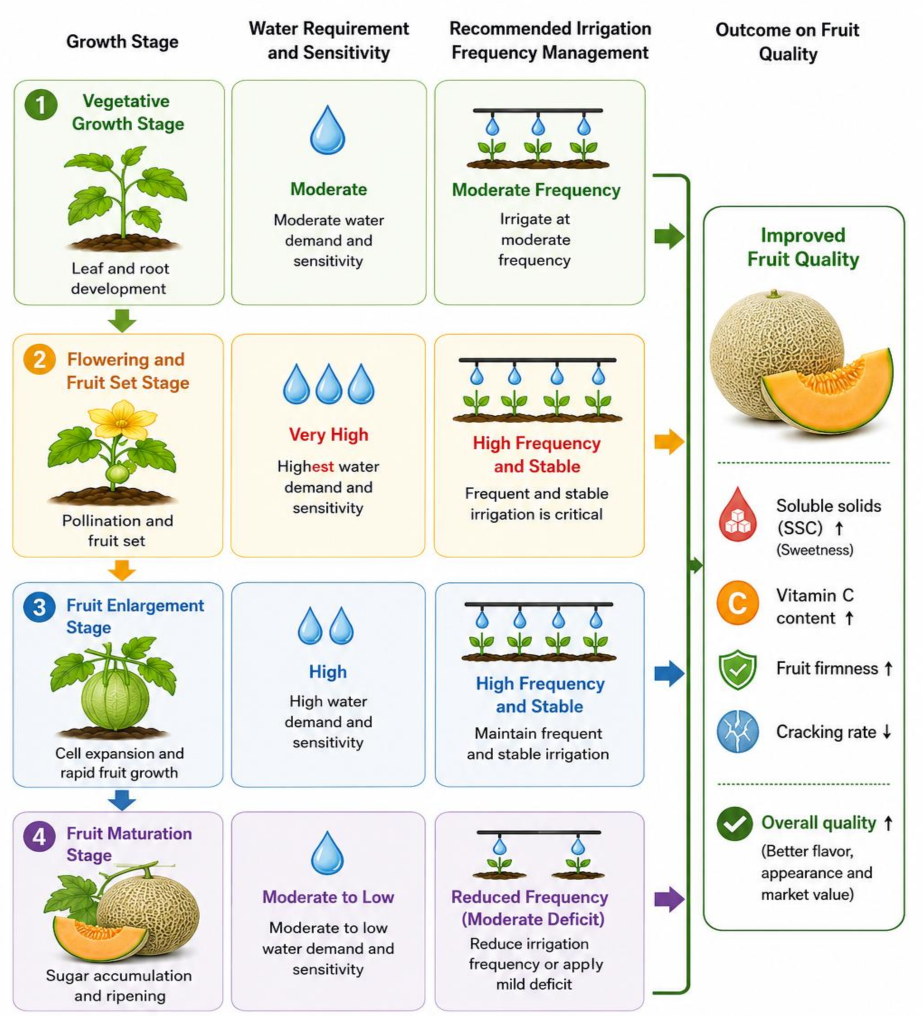

Figure 1 Framework of water sensitivity and irrigation frequency management across melon growth stages

3 Effects of Irrigation Frequency on Melon Growth

3.1 Influence on plant height and biomass accumulation

Vegetative growth is usually the first visible response to irrigation frequency. When irrigation is delivered in smaller, more frequent doses under drip systems, the root zone tends to experience fewer sharp moisture fluctuations, which often supports taller plants, thicker stems, higher fresh mass, and greater dry matter accumulation. In a net-house study from Cambodia, three drip irrigations per day produced the greatest plant height, stem diameter, biomass accumulation, and yield relative to one or two irrigations per day and hand watering, despite equal total water based on crop requirement. This is a useful reminder that frequency can change plant performance even when the seasonal water amount is similar (Nut et al., 2019).

Open-field evidence points in the same direction, although the optimum interval depends on climate and soil. Sensoy and colleagues found that a 6-day schedule with higher pan-based replacement produced the highest melon yield and strongly affected fruit traits, indicating that lower frequency combined with lower replacement was too restrictive. Similarly, greenhouse studies in southeast China have shown that low-water treatments can increase some quality attributes, but they also lower biomass accumulation and tend to suppress maximal yield. The main message is that adequate growth depends on keeping vegetative stress within a narrow range (Sensoy et al., 2007; Yue et al., 2023).

3.2 Effects on root development and water uptake

Root responses to irrigation frequency are more complex than shoot responses. In field-grown crops, less frequent irrigation can sometimes encourage deeper rooting, but in high-value melon systems, especially greenhouses and substrates, large drying cycles often reduce effective water uptake before any benefit from "hardening" appears. A recent cantaloupe study found that severe deficit weakened plant water status enough to trigger water-conservative behavior, while also suggesting reduced root hydraulic conductivity under stronger soil drying. By contrast, moderate deficit maintained functional performance much better (di Santo and Barrios-Masias, 2026).

Protected-environment studies show that root-zone physical conditions matter alongside watering rhythm. In a BMC Plant Biology study on greenhouse muskmelon, supplemental soil aeration under subsurface drip increased yield, leaf area index, dry matter, and irrigation use efficiency, showing that water-frequency effects cannot be separated from oxygen supply in the root zone. In other words, a frequent irrigation schedule is beneficial only if it avoids hypoxia and keeps the wetting pattern accessible to roots (Li et al., 2020).

Northwestern China adds another layer because high-EC irrigation water and protected production often require pulsed delivery rather than a few large applications. Sun and colleagues found that, in high-EC irrigation regions, irrigation frequency had a curvilinear effect, with integrated growth, water use efficiency, fertilizer use efficiency, and fruit quality improving and then declining as frequency increased; across their tested conditions, seven pulses per day emerged as the best compromise. This result is especially revealing because it shows that "more frequent" is not always better. There is an optimum beyond which additional pulsing adds management complexity without physiological gain (Sun et al., 2024).

3.3 Effects on leaf growth and photosynthetic performance

Leaf area is central to melon productivity because the fruit depends on a continuous supply of current photoassimilates rather than large stored reserves. Studies under deficit irrigation repeatedly show that reduced water availability lowers relative water content, stomatal conductance, and net photosynthesis, which then limits leaf expansion and canopy persistence. In inoculated and uninoculated melon plants, Miceli and colleagues observed that stronger deficits reduced stomatal conductance and fruit yield, while moderate deficit combined with mycorrhiza improved water use efficiency and preserved some quality traits (Miceli et al., 2023).

The same physiological pattern appears outside Mediterranean systems. Panda and colleagues reported that increasing water stress in a Mediterranean climate reduced yield and fruit traits and that the best outcomes for relative water content, stomatal conductance, and yield were associated with full irrigation and the milder reduction level. In Murcia, sensor-based precision irrigation improved water productivity without depressing stem water potential, photosynthesis, or stomatal conductance, suggesting that irrigation frequency can be reduced or adjusted only when plant status is monitored carefully enough to avoid a hidden physiological penalty. (Zapata-García et al., 2023; Panda et al., 2025).

3.4 Comparative responses under different irrigation frequencies

Taken together, the comparative literature suggests that the "best" irrigation frequency depends on production environment. In greenhouse and nethouse systems with localized drip or substrate culture, relatively frequent or pulsed irrigation often performs better because the effective root volume is smaller and the system dries quickly. That is why three irrigations per day improved growth under net-house conditions, and why seven pulses per day performed well in the high-EC greenhouse study from northwestern China (Nut et al., 2019; Sun et al., 2024).

In open-field systems, however, medium intervals can be appropriate when water amount is sufficient and soil water storage is greater. Sensoy's field study showed that 6-day irrigation outperformed a 12-day interval, but that does not mean "daily" irrigation is always needed outside a greenhouse. The broader point is that irrigation frequency must be interpreted relative to rooting depth, evaporative demand, substrate volume, and water quality. Reviews and greenhouse-irrigation syntheses increasingly argue that the real goal is not a fixed interval but a frequency that keeps plants away from both acute stress and prolonged oversupply (Figure 2) (Sensoy et al., 2007; Nikolaou et al., 2019; Fang et al., 2026).

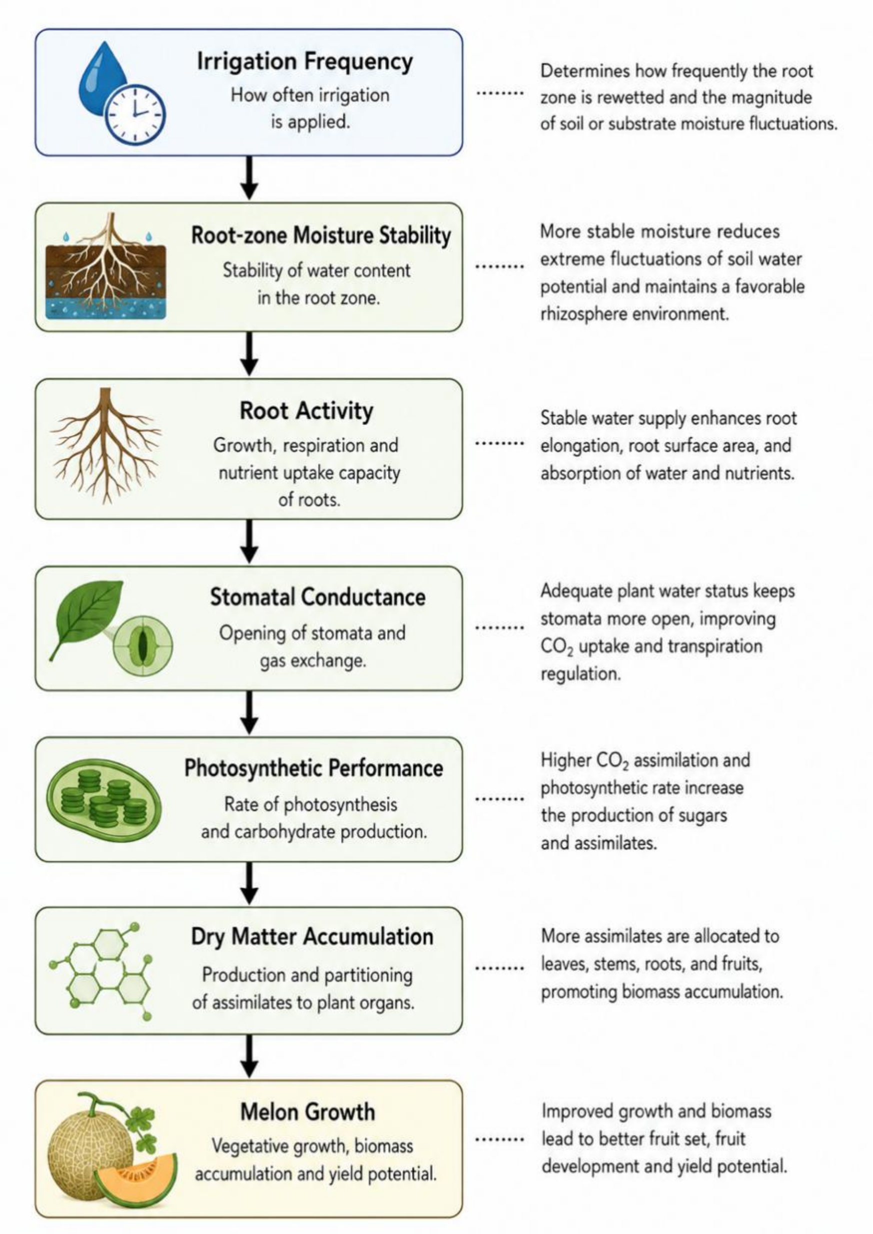

Figure 2 Physiological pathway through which irrigation frequency regulates melon growth

4 Effects of Irrigation Frequency on Fruit Development

4.1 Fruit set and early fruit growth

Fruit development begins with a fragile transition. At flowering and immediately after fruit set, the plant is deciding how many fruits it can support, and the developing fruit is establishing its sink strength through active cell division and early expansion. Water deficits at this stage can therefore reduce more than final fruit size; they can reduce the basic developmental capacity of the crop to produce marketable fruit. This principle has been clear since early controlled-deficit work, and it remains visible in current studies. Fabeiro and colleagues showed that deficits during blooming had the lowest production, while Yavuz and colleagues found that treatments depriving the crop of stable water during reproductive development significantly reduced yield (Fabeiro et al., 2002; Yavuz et al., 2021).

Even in protected environments where daily irrigation can be precisely delivered, unstable moisture at this stage can be costly. The 2019 net-house experiment showed that more frequent drip events supported stronger vegetative development and higher yield, which likely reflects better protection of early sink establishment as well as better canopy support. More recent physiological work also indicates that flowering to early fruit enlargement is the point at which drops in plant water status can quickly translate into reduced stomatal conductance and weaker assimilate supply (Nut et al., 2019; di Santo and Barrios-Masias, 2026).

4.2 Fruit enlargement and weight accumulation

During enlargement, melon fruits become strong sinks for both water and carbon. This is the stage when irrigation frequency most directly affects fresh weight and marketable size. Field and greenhouse studies are remarkably consistent on this point: adequate irrigation during enlargement increases fruit weight, whereas stronger deficits reduce it. In the Haining greenhouse trial, higher water input increased yield, although the middle irrigation treatment proved better overall once quality and efficiency were considered. In Turkey, the highest average yields were achieved either with full irrigation or with a regime that delayed deficit until ripening, which implies that fruit enlargement was still protected by adequate water (Kuscu and Turhan, 2022; Yue et al., 2023).

Severe deficits during or before enlargement can also shrink fruit in greenhouse systems. The 2025 greenhouse muskmelon study found that deficits applied across both flowering-swelling and maturity stages reduced fresh and dry fruit weight, while field work in Nevada showed that severe deficit at 50% field capacity lowered yield by about 40% relative to full irrigation. These findings suggest that there is little agronomic value in letting fruit experience strong and repeated water shortages while they are still building mass (Xue et al., 2025; di Santo and Barrios-Masias, 2026).

4.3 Fruit maturation and ripening characteristics

The maturation stage is where irrigation frequency changes from being mainly a yield-management variable to being a quality-management variable. Many studies show that reducing irrigation or frequency late in development can raise soluble solids, improve the sugar–acid balance, and reduce disorders such as cracking. In northwestern China, Xue and colleagues found that mild deficit during maturity sharply reduced greenhouse muskmelon cracking while maintaining yield and improving quality. In Turkey, water stress treatments often improved quality traits even when they lowered yield, again indicating that the end of the cycle is the most responsive stage for targeted quality enhancement (Yavuz et al., 2021; Kuscu and Turhan, 2022; Xue et al., 2025).

The effect is not unlimited, however. If late deficit is too strong, fruit size and commercial acceptability can still decline. In Taiwan, Fang and colleagues reported that a plant-based regulated deficit strategy improved sweetness and reduced cracking in soilless systems, but it also reduced yield and fruit size there, while in soil-grown systems the same framework reduced irrigation by 19.3%-25.7% without compromising yield or fruit quality. This contrast is valuable because it shows that the same late-season deficit principle behaves differently in soil and soilless environments (Fang et al., 2026).

4.4 Physiological mechanisms linking water supply and fruit development

The physiological link between irrigation frequency and fruit development can be summarized in four connected steps. First, irrigation rhythm determines how stable soil or substrate moisture remains in the root zone. Second, root-zone stability shapes plant water status, stomatal behavior, and nutrient transport. Third, those whole-plant responses govern the amount and continuity of carbon and water delivered to the fruit. Fourth, fruit tissues translate those inputs into cell division, cell expansion, sugar concentration, acid metabolism, and mechanical integrity. This is why a small change in watering schedule can alter not just fruit size, but also cracking, sweetness, and firmness (Cheng et al., 2022; Gustani et al., 2024; Wang et al., 2025).

Melon fruit quality biology helps explain the stage effect. Integrated transcriptomic and metabolomic studies show that sucrose, glucose, organic-acid metabolism, and texture-related pathways all shift sharply across development and ripening. A review of melon firmness mechanisms similarly emphasizes that cell-wall remodeling during maturation is a major determinant of softening and storability. Therefore, when late irrigation frequency is reduced and fruit water influx becomes slightly more restricted, sugar concentration may rise and cracking pressure may fall, but if the stress is too strong, the fruit can lose mass and uniformity instead (Cheng et al., 2022; Gustani et al., 2024; Liu et al., 2024).

5 Effects of Irrigation Frequency on Fruit Quality

5.1 Soluble solids and sugar accumulation

Soluble solids concentration is the quality trait most consistently improved by mild water restriction in melon. This does not mean that drought “creates” sugar in a simple way. More often, reduced late-stage water supply limits further dilution and alters carbohydrate partitioning so that the concentration of sugars in the flesh becomes higher. In the Haining, Zhejiang greenhouse study, lower water treatments produced higher total soluble solids and vitamin C than the medium and high water treatments, even though they did not maximize yield. In the maturity-deficit study from China, mild deficit increased sugar-related quality and lowered cracking risk (Yue et al., 2023; Xue et al., 2025).

The pattern appears in other regions as well. Kuscu and Turhan reported that deficit treatments significantly affected soluble solids, total sugar, titratable acidity, vitamin C, and protein content, with quality traits generally improving under deficit irrigation. Miceli and colleagues similarly observed that moderate deficit combined with arbuscular mycorrhizal inoculation improved fruit soluble solids and the SSC/TA ratio. These results show why growers often accept slightly lower vegetative vigor or even a small yield penalty when the market strongly rewards sweetness (Figure 3) (Kuscu and Turhan, 2022; Miceli et al., 2023).

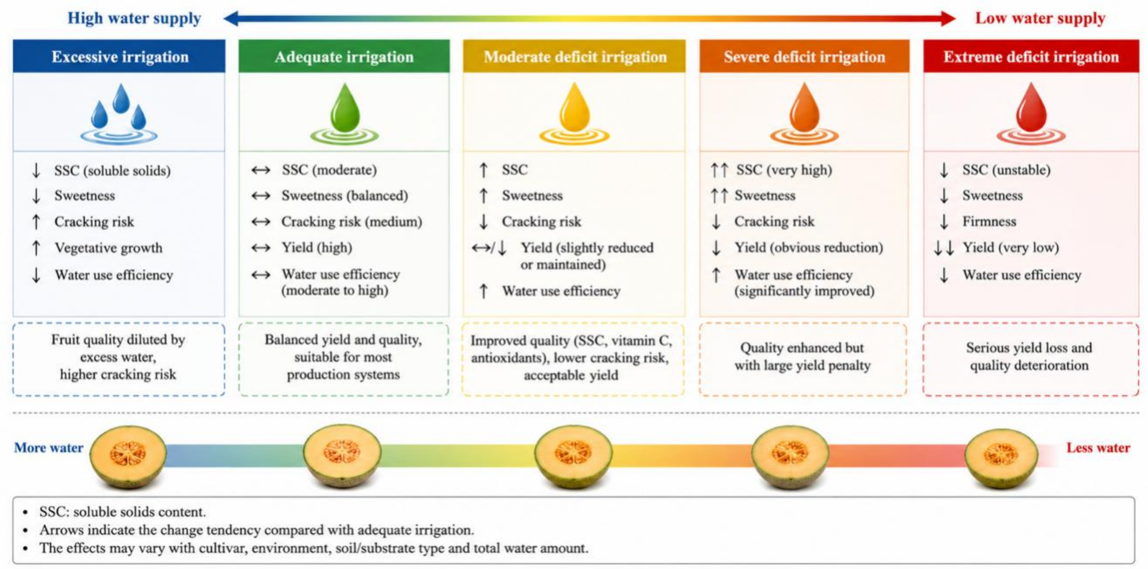

Figure 3 Quality formation of melon fruits under different water supply regimes

5.2 Organic acids and flavor formation

Flavor depends on more than sweetness. Organic acids help determine freshness, balance, and overall sensory character, and melon flavor is also shaped by volatile compounds that change across development and storage. Irrigation regime affects these traits by changing dilution, carbon metabolism, and ripening status. In a 2023 study of melon flesh and seeds under different irrigation regimes, sucrose, total sugar, titratable acidity, phenolic compounds, and antioxidant activity all responded significantly to how and when water was supplied. Notably, some deficit treatments improved phenolics and antioxidant activity while also shifting sugar composition (Ercan et al., 2023).

Molecular studies help explain why this happens. A Frontiers study comparing oriental melon cultivars found that sugar and organic-acid accumulation are developmentally regulated and tied to differential gene networks, while a 2024 maturity study showed strong changes in sucrose, citric acid, and related processes between 60% and 90% maturity fruit. From a practical perspective, this means irrigation frequency affects flavor most strongly when it modifies the developmental environment in which these pathways operate, especially late in fruit growth (Cheng et al., 2022; Liu et al., 2024).

5.3 Fruit firmness and shelf-life characteristics

Fruit firmness is a major commercial trait because it influences transport tolerance, shelf life, and susceptibility to mechanical damage and cracking. Irrigation affects firmness in two ways. First, it changes turgor and tissue hydration during growth. Second, it alters the pace of maturation and cell-wall remodeling. In greenhouse muskmelon, mild deficit during maturity reduced cracking substantially and improved the commercial balance between yield and quality, while a 2026 regulated deficit irrigation framework in Taiwan improved sweetness and reduced fruit cracking in soilless systems, even though yield trade-offs were observed (Xue et al., 2025; Fang et al., 2026).

The mechanistic literature adds depth to these agronomic findings. A recent review on melon firmness emphasized that maturation-related expression of cell-wall genes is central to texture loss and shelf-life decline. When irrigation is too frequent or too abundant late in the season, fruits may remain larger but structurally more vulnerable. When stress is mild and well-timed, fruits may become firmer, less crack-prone, and easier to store. In the mycorrhiza study, moderate deficit with AMF increased firmness and improved some quality traits, reinforcing the idea that firmness can be managed not only by less water, but by better physiological resilience (Miceli et al., 2023; Gustani et al., 2024).

5.4 Nutritional quality and bioactive compounds

Nutritional quality traits such as vitamin C, phenolics, antioxidant activity, and related bioactive compounds often rise under moderate water restriction. This pattern appears repeatedly in recent melon studies, although the response depends on cultivar, stage, and stress intensity. In Zhejiang, lower irrigation increased vitamin C in greenhouse muskmelon. In Murcia, sensor-based precision irrigation increased ascorbic acid by about one-third on average while also conserving water and improving water and nitrogen productivity. In the irrigation-regime quality study, deficit timing changed phenolic content and antioxidant activity as well as sugars (Ercan et al., 2023; Yue et al., 2023; Zapata-García et al., 2023).

This does not mean stronger stress always improves nutrition. Severe or poorly timed deficits can reduce size, yield, and sometimes firmness, which can offset any gain in concentration. The better interpretation is that mild, controlled deficit near the end of the fruit cycle often shifts fruit composition toward a denser nutritional and sensory profile. The biostimulation study strengthens this idea, because fruit from the biostimulated deficit treatment had higher phenolic concentration than fruit under precision irrigation alone (Zapata-García et al., 2025).

6 Representative Case Studies of Irrigation Management in Melon Production

6.1 Protected melon production in eastern china: implications for zhejiang province

For an author working from Zhejiang, the strongest directly relevant English-language case is the two-year greenhouse muskmelon experiment carried out in Haining, Zhejiang. The study tested three irrigation levels based on ETc and three nitrogen levels and concluded that the combination of 1.0 ETc with 95 kg N ha^{-1} achieved the best compromise among yield, quality, irrigation water use efficiency, and nitrogen use efficiency. Low-water treatments improved vitamin C and soluble solids, but the balanced treatment was superior overall for production under local protected conditions. Because the work was conducted in Haining under a north subtropical monsoon climate and by a Zhejiang-based research team, it is especially appropriate as a regional anchor for review writing aimed at eastern China (Yue et al., 2023).

This case is valuable for another reason. It shows that, in humid and commercially intensive protected systems, the question is rarely whether less water improves sweetness. The real question is how to avoid the common farmer tendency toward excessive irrigation and fertilization while still keeping yield high enough for commercial greenhouse production. The Haining results suggest that irrigation in this region should be moderate rather than maximal, and that water scheduling should be coupled with nutrient management instead of treated independently. That conclusion fits well with the production realities of Zhejiang, where growers often target appearance and quality premiums in protected fruit (Yue et al., 2023).

6.2 Greenhouse melon irrigation management in the yangtze river delta region

Direct English-language field studies explicitly framed as "Yangtze River Delta melon irrigation" are still relatively limited, which is itself an important observation. However, existing evidence from the broader region still gives a useful picture. The Haining greenhouse case already belongs to the Delta's eastern protected-horticulture context, and a Shanghai-based study on greenhouse netted muskmelon demonstrated that plant phenotyping and random-forest modeling could forecast substrate water status with high stage-specific accuracy, reaching 77.60%, 94.37%, and 90.01% at seedling, vine elongation, and fruit development stages, respectively. That work matters because greenhouse melon systems in the Delta are often technologically intensive and quality-oriented, making plant-based irrigation decision tools especially relevant (Chang et al., 2019; Yue et al., 2023).

The practical lesson for the Yangtze River Delta is not that every farm should adopt machine learning immediately. It is that regional melon systems are well suited to dynamic irrigation scheduling because they combine protected cultivation, high fruit value, and relatively strong technical infrastructure. In such a context, irrigation frequency can reasonably move away from fixed grower habit toward stage-specific decision rules tied to substrate water status, crop growth stage, and desired fruit quality. What is still missing is more field-validated, English-language, region-specific work that links these tools to final fruit quality and economic return under Delta humidity and greenhouse conditions (Chang et al., 2019; Fang et al., 2026).

6.3 Deficit irrigation practices in northwestern china

Northwestern China provides a contrasting environment in which water scarcity, salinity risk, and greenhouse or substrate production make irrigation frequency an even more technical issue. Sun and colleagues, working in high-EC irrigation water regions, evaluated irrigation amount, nutrient solution EC, and irrigation frequency together and found that integrated growth and efficiency rose and then fell with frequency, with seven irrigations per day emerging as the best option in their studied conditions. This is a clear case where pulsed irrigation is not merely a convenience; it is a way to manage salinity, root-zone conditions, and plant performance simultaneously (Sun et al., 2024).

Another northwestern case comes from soil-moisture-based furrow irrigation scheduling for melon in an arid region, which showed that moisture-based scheduling can improve the balance between yield and quality under water limitation. More recently, greenhouse substrate work found that mild deficit during fruit maturity significantly reduced cracking and improved fruit quality. Together, these studies show that northwestern systems often need two things at once: water-saving delivery and stage-targeted quality management. The frequency question therefore becomes highly practical—how small and how often should irrigation events be when water is limited but fruit quality must remain premium? (Wang et al., 2017; Xue et al., 2025).

6.4 Lessons from regional melon production systems

Across regions, one broad lesson stands out: irrigation frequency is not transferable in a simple calendar form. Humid eastern greenhouses, high-tech Delta systems, arid northwestern greenhouses, Mediterranean open fields, and North American semi-arid field systems all respond differently because evaporative demand, rooting volume, salinity, and market goals differ. Yet a common rule still emerges. Fruit set and enlargement need stable moisture; ripening can tolerate, and often benefit from, controlled reduction (Fabeiro et al., 2002; Kuscu and Turhan, 2022; Fang et al., 2026).

A second lesson is methodological. Regional case studies that treat frequency together with root-zone environment, nutrient supply, and plant status are more informative than studies that vary only seasonal water amount. This is why the Zhejiang greenhouse trial, the Shanghai phenotyping model, the northwestern pulsed-irrigation study, and the Taiwan plant-based RDI framework are especially useful references for a modern review. They move the discussion from "how much water?" to "how should the plant experience water over time?" (Chang et al., 2019; Yue et al., 2023; Sun et al., 2024; Fang et al., 2026).

7 Sustainable Irrigation Strategies for Improving Growth and Fruit Quality

7.1 Drip irrigation and water-saving technologies

Drip irrigation remains the most important base technology for melon water management because it allows both amount and frequency to be controlled accurately. The literature generally shows that drip systems outperform furrow or less localized methods in water use efficiency and often in yield when managed well. A recent northeastern/northern China study reported that plastic-mulched drip irrigation produced the highest greenhouse melon yield and sharply reduced water consumption relative to furrow-based control treatments. This confirms that the irrigation method itself conditions how frequency affects the crop (Liu et al., 2024).

Additional water-saving technologies refine this basic system. Subsurface drip can reshape the wetting pattern and reduce evaporation, but root-zone aeration may be needed to avoid oxygen limitations. Mulching reduces surface evaporation and stabilizes temperature, which often allows fewer or smaller irrigations without stronger plant stress. Reviews of greenhouse irrigation therefore emphasize that "efficient irrigation" is rarely a single device; it is a package that combines localized delivery, evaporation control, and scheduling logic (Nikolaou et al., 2019; Li et al., 2020).

7.2 Precision irrigation and smart agriculture

Precision irrigation is the natural next step because melon responds so strongly to stage and water status. Recent studies offer three promising routes. The first uses soil or substrate sensors to regulate irrigation based on allowable depletion, as in the Murcia studies that reduced water use and leaching while preserving yield. The second uses plant phenotyping or image-based information, as shown in the Shanghai muskmelon forecasting study. The third uses direct plant-based thresholds and crop coefficient calculations, as demonstrated by Fang and colleagues in Taiwan (Chang et al., 2019; Zapata-García et al., 2023; Fang et al., 2026).

These systems are attractive because they convert irrigation frequency from a calendar habit into a crop-response decision. Still, most are not yet effortless for commercial use. Plant-based monitoring can be expensive, image acquisition can be sensitive to greenhouse conditions, and some models still require manual or highly standardized measurements. Even so, the direction is clear: the future of melon irrigation lies in adaptive rather than fixed scheduling (Chang et al., 2019; Fang et al., 2026).

7.3 Integration of irrigation and nutrient management

For melon, irrigation frequency should rarely be discussed without nutrient management. Frequent irrigation changes nutrient residence time, fertigation uniformity, and leaching risk, while nutrient level changes the crop's ability to convert water into biomass and fruit. The Zhejiang greenhouse case showed that water and nitrogen had to be optimized together, not separately. Likewise, the northwestern high-EC study identified the optimum only when irrigation amount, nutrient-solution EC, and irrigation frequency were evaluated jointly (Yue et al., 2023; Sun et al., 2024).

The same principle appears in commercial-scale precision irrigation. Zapata-García and colleagues demonstrated that sensor-guided irrigation reduced water use while improving both water and nitrogen productivity, meaning that the gain was not simply "less water," but a better synchronization of water, root-zone retention, and nutrient availability. Biological complements may also help. In melon grown under deficit irrigation, AMF inoculation improved some quality traits and water-use indicators, which suggests that sustainable irrigation strategies can include microbial support as well as digital control (Miceli et al., 2023; Zapata-García et al., 2023).

7.4 Improving water use efficiency under climate change

Climate change intensifies the need to improve water use efficiency because higher evaporative demand makes fixed irrigation calendars less reliable. The broad vegetable literature suggests that moderate deficit irrigation often increases water productivity more reliably than severe deficit, but melon-specific work refines that conclusion by showing that deficit intensity must be matched to growth stage. Moderate deficit can be useful; severe, prolonged deficit frequently damages yield or fruit size (Singh et al., 2021; Panda et al., 2025; di Santo and Barrios-Masias, 2026).

Under climate uncertainty, the most resilient strategy for melon is probably a flexible system with three features: drip-based localized delivery, stage-specific irrigation frequency, and real-time adjustment by soil, substrate, or plant indicators. The recent Taiwan greenhouse study is particularly persuasive here because it reduced irrigation by about one-fifth to one-quarter in soil-grown systems without sacrificing yield or fruit quality. That is the kind of evidence needed for climate-adaptation arguments: not abstract efficiency, but water saving with maintained commercial output (Fang et al., 2026).

8 Future Perspectives and Conclusions

8.1 Current limitations in irrigation frequency research

Despite the growing literature, research on melon irrigation frequency still has several limitations. Many studies change both irrigation amount and frequency at the same time, which makes it difficult to isolate the independent effect of frequency. Others are highly system-specific, meaning that results from open-field loam soils cannot be transferred directly to substrate bags or peat-based troughs. Another limitation is that cultivar type is often underemphasized even though climacteric versus non-climacteric behavior, fruit size, netting, and cracking susceptibility may all influence the response to water scheduling (Singh et al., 2021; Xue et al., 2025; Fang et al., 2026).

There is also a regional imbalance in the evidence base. Semi-arid and water-limited regions are relatively well represented, but humid protected systems in eastern China, especially those typical of the Yangtze River Delta, still lack abundant English-language studies devoted specifically to irrigation frequency in melon. As a result, growers in these regions often have to infer management rules from studies designed for other climates or from experiments where water amount rather than frequency was the main focus (Chang et al., 2019; Yue et al., 2023).

8.2 Emerging technologies for irrigation management

The most promising new technologies are those that transform irrigation scheduling into a real-time, stage-aware process. Plant phenotyping, machine learning, soil-water sensors, plant water-status classification, and decision frameworks that combine crop coefficients with physiological thresholds have all reached a point where they can support serious greenhouse management. Their value is not only higher precision. They also make it possible to apply different irrigation frequencies at different stages without relying on intuition alone (Chang et al., 2019; Zapata-García et al., 2023; Fang et al., 2026).

At the same time, these technologies still need simplification. Models that depend on expensive instruments or highly standardized imaging environments are harder to scale commercially. The next practical gains will likely come from lower-cost sensors, easier interfaces, and integrated platforms that link environmental monitoring, crop stage recognition, and fertigation control in one system. For melon, this integrated approach is especially promising because quality and cracking risk respond so strongly to late-season water management (Zapata-García et al., 2025; Fang et al., 2026).

8.3 Future research directions

Future melon research should do three things more clearly. First, it should separate irrigation frequency from total water amount by using experiments in which seasonal water is held constant while interval or pulse structure changes. Second, it should compare responses across cultivars and production systems so that recommendations become more transferable. Third, it should move beyond yield and soluble solids to include cracking rate, firmness, aroma, shelf life, and economic return, because these are often the traits that determine whether a water-saving schedule is commercially acceptable (Sensoy et al., 2007; Xue et al., 2025; Fang et al., 2026).

For eastern China and especially for Zhejiang-related production, more local greenhouse work is needed. The Haining study gives a strong starting point, but it does not answer every question about irrigation frequency under the humid, quality-oriented, protected systems common in the region. Future trials should compare daily versus pulsed scheduling, link irrigation rhythm with fruit cracking and flavor, and test whether sensor-based models developed in one Delta greenhouse can be transferred to another. That would make irrigation recommendations not only more scientific, but more regionally useful (Chang et al., 2019; Yue et al., 2023).

8.4 Conclusions

Irrigation frequency is one of the most practical and biologically meaningful levers in melon production. It shapes vegetative growth through its effects on root-zone stability, leaf expansion, and photosynthesis. It shapes fruit development by protecting or constraining fruit set and enlargement. And it shapes fruit quality by influencing sugar concentration, acidity, firmness, nutritional compounds, and cracking during maturation. The strongest overall pattern in the literature is not that frequent irrigation is always better or that deficit is always better. Rather, melon performs best when irrigation frequency changes with developmental stage.

Stable and adequate watering is most important from flowering through early fruit growth. This is the phase where poor scheduling most clearly reduces yield. Later, once fruit size is largely formed, a carefully controlled reduction in frequency or intensity can improve sweetness, nutritional density, and market quality, and may also reduce cracking. Greenhouse systems, soilless culture, and high-value protected production make this stage-specific logic even more important because the root zone is smaller and fruit quality premiums are higher.

Viewed this way, irrigation frequency is not simply a timing parameter. It is a developmental strategy. Good melon irrigation should therefore be dynamic, stage-specific, and increasingly data-informed. For growers and researchers alike, the practical goal is no longer just to apply enough water. It is to deliver water with the right rhythm, at the right stage, for the right fruit outcome.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Effects of Trellis Systems on Yield and Fruit Quality of Luffa

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Abstract Sponge gourd (*Luffa cylindrica*) is an important cucurbit vegetable widely cultivated in tropical and subtropical regions due to its high nutritional value and economic significance. Trellising cultivation is a key agronomic practice that influences plant architecture, canopy microclimate, resource utilization efficiency, and ultimately fruit yield and quality. Different trellising systems, including horizontal pergola, A-frame, fence, and vertical training systems, create distinct growing environments that affect photosynthesis, flowering, fruit set, and assimilate partitioning. This review summarizes the biological characteristics of sponge gourd and the theoretical basis of trellising cultivation, and examines the effects of various trellising systems on plant growth, yield formation, fruit quality, and production efficiency. Furthermore, representative case studies are analyzed to compare the performance of different trellis configurations under diverse cultivation conditions. The economic and ecological benefits of trellising cultivation, including labor efficiency, disease management, and sustainable production, are also discussed. Current research limitations and future directions, such as the development of innovative and intelligent trellising technologies, are highlighted. This review provides a comprehensive reference for optimizing sponge gourd cultivation practices and improving productivity and fruit quality in sustainable horticultural systems.
Keywords Sponge gourd; Trellising system; Yield formation; Fruit quality; Sustainable cultivation

1 Introduction

Sponge gourd (*Luffa cylindrica*) is an emerging, climate-smart cucurbit with growing importance for both food and industrial fiber. It is described as an “emerging high potential crop in Asia” but remains underutilized in many regions, with farmers often relying on traditional practices and limited technical guidance on morphology, floral biology, and yield optimization. Beyond its role as a vegetable, sponge gourd provides plant-based fiber and is highlighted as a niche “opportunity crop” with multiple utilities in food and industrial sectors, yet still undervalued due to limited research and product development (Mashilo et al., 2025). Reviews also emphasize increasing interest driven by health benefits, climate resilience, and market demand, and call for improved agronomic packages and high-yielding varieties to support commercialization at local and international levels.

In Sri Lanka and other producing areas, yields remain constrained by poor management; for example, farmers often allow vines to trail on fences or the ground, practices that are associated with reduced yield and fruit quality and lack of systematic trellis use. At the same time, multivariate and varietal studies show substantial genetic variability for yield, nutritional traits, and quality in sponge gourd, underscoring the crop’s potential if supported by suitable production technologies (Chithra et al., 2024). Within cucurbit production systems more broadly, trellising has become a key cultural practice to intensify production, improve canopy microclimate, and enhance yield and marketable quality. In cucumber, trellised plants show consistently taller vines, larger leaves, more leaves, and higher marketable yield than untrellised plants, along with reductions in non-marketable fruits. Classic studies comparing trellis versus ground culture in field cucumber reported up to 100% increases in marketable yield under trellising, with more uniform dark-green fruits, higher Fancy grades, and fewer culls. Trellising also facilitated better control of foliar and fruit diseases by improving aeration, reducing humidity, and allowing more effective fungicide coverage. In hydroponic Beit Alpha cucumber grown in low-profile greenhouses, comparisons of high-wire and modified-umbrella systems showed that trellis architecture can shift the balance between total fruit number and yield consistency, suggesting that trellis design must be matched to growers’ yield and labor objectives.

Beyond cucurbits, perennial climbing fruit crops such as passion fruit also rely heavily on support systems, where simple trellis arrangements have been associated with the highest productivity and superior fruit quality compared with more complex “T” and total trellis systems. For sponge gourd specifically, trellising and training systems are increasingly recognized as central components of improved production technology, yet their effects on yield and fruit quality are still being defined. In Sri Lankan sponge gourd, evaluation of three trellising methods showed that horizontal trellising was “ideal” under local conditions, achieving an average yield of 8.4 t ha^{-1}; trellis type did not significantly change fruit length and diameter, but did significantly alter fruit number per plant.

A recent study comparing four above-ground training systems—bower, single plant training, netting, and ground trailing—found that bower trellising produced the maximum yield, fruits per plant, fruit length, fruit width, and vine length, with substantial percentage yield increases of up to 71% over ground trailing, further supporting the value of structured support for sponge gourd vines. In subtropical Mexico, open-field sponge gourd cultivation with “trellis mesh” oriented to optimize light exposure and row spacing tailored to the long vines has been shown to support good yields and efficient management, and even allows the use of circular trellis designs to maximize space. Related work in ridge gourd, another Luffa species, demonstrates that different trellis geometries (e.g., pandal versus T-trellis) affect not only yield and benefit-cost ratio but also fruit quality traits, implying that trellis system choice can be a fine-tuning tool for both productivity and market value in Luffa crops.

2 Cultivation Characteristics of Sponge Gourd and Theoretical Basis of Trellising

Overall, sponge gourd has high but underexploited agronomic and economic potential, and trellising is a critical, yet still inadequately optimized, component of its cultivation. Evidence from sponge gourd and related cucurbits indicates that well-designed trellis systems can substantially increase yield, improve fruit quality, and facilitate disease and crop management. However, the specific effects of different trellis architectures on sponge gourd yield components and quality traits remain insufficiently characterized, justifying focused research on the effects of trellis systems on yield and fruit quality of Luffa.

2.1 Biological characteristics and growth requirements of sponge gourd

Sponge gourd (*Luffa cylindrica*) is a monoecious cucurbit bearing separate male and female flowers on the same plant, with flowering starting about 6-7 weeks after seeding and an initially high proportion of male flowers. The crop produces long climbing vines and cylindrical fruits which, when fully mature and dried, form fibrous sponges typically 17-20 cm in length with densely arranged fibers. As a short-day species, sponge gourd thrives under cool temperatures and shorter photoperiods, with kharif conditions providing particularly favorable environments for vigorous vegetative growth, flowering, and fruit set (Vidya et al., 2025). Growth and yield are also shaped by soil and nutrient conditions.

In subtropical Mexico, plants established by direct seeding on fertile Luvisols amended with an organo-mineral substrate reached vine lengths of nearly 39 m and produced 5-20 fruits per plant, whereas plants on less fertile Andosols showed shorter vines and lower fruit size and weight (Fernández-Lambert et al., 2025). Optimized fertilization regimes combining reduced mineral N and P with K and bio-fertilizers have produced vine lengths around 2.8 m, earlier flowering, and yields up to 30.8 t ha^{-1} together with improved fruit quality traits such as higher soluble solids and ascorbic acid.

2.2 Vine growth patterns and spatial distribution characteristics

As a climbing cucurbit, sponge gourd exhibits vigorous, indeterminate vine growth with substantial variation in vine length and branching among genotypes and environments. In seasonal evaluations, individual inbred lines have produced vines exceeding 8 m in length with high numbers of branches and extended harvest durations, illustrating the inherently expansive canopy potential of this crop (Vidya et al., 2025). Direct-sown plants in open-field systems have attained mean plant lengths above 30 m, reflecting an ability to explore large horizontal or vertical spaces when physical support and resources are not limiting. Early establishment factors such as shallow sowing depth promote more vigorous vine elongation and leaf development, indicating that initial root–shoot balance and resource capture strongly influence later canopy expansion.

Cucurbit vine architecture is also shaped by genetic regulation of branching, tendril development, and shoot indeterminacy. In cucumber, a model cucurbit, shoot architecture is determined by coordinated control of branch outgrowth, tendril identity, and vine length, with leaves and flowers produced continuously from axillary meristems along the vine. Comparative phylotranscriptomic work in Cucurbitaceae shows that specialized tendrils and climbing habit are linked to a cucurbit-specific tendril identity gene, reflecting evolutionary innovation that enables vertical exploration of surrounding vegetation and supports (Guo et al., 2020). These genetic and anatomical features underpin the ability of sponge gourd vines to distribute foliage and fruits three-dimensionally, but without deliberate training they often trail along fences or the ground, leading to suboptimal spatial distribution and compromised yield and quality.

2.3 Ecological and agronomic principles of trellising cultivation

Trellising modifies the ecological environment experienced by sponge gourd canopies by altering light distribution, air movement, and plant-soil interactions. In general crop canopies, modern management seeks to optimize stand-level light use efficiency rather than individual plant competitiveness, with canopy modeling highlighting that more uniform light distribution within the canopy can improve productivity and close yield gaps. Studies in trellised orchard systems show that espalier-type training can enhance light distribution efficiency per unit leaf area, although total productivity then depends on the balance between leaf area and light interception. Applied to climbing vegetables, trellis structures create vertically layered foliage where upper leaves intercept direct radiation while lower leaves receive filtered light, supporting photosynthesis throughout the canopy and improving microclimatic conditions for flowers and fruits (Figure 1).

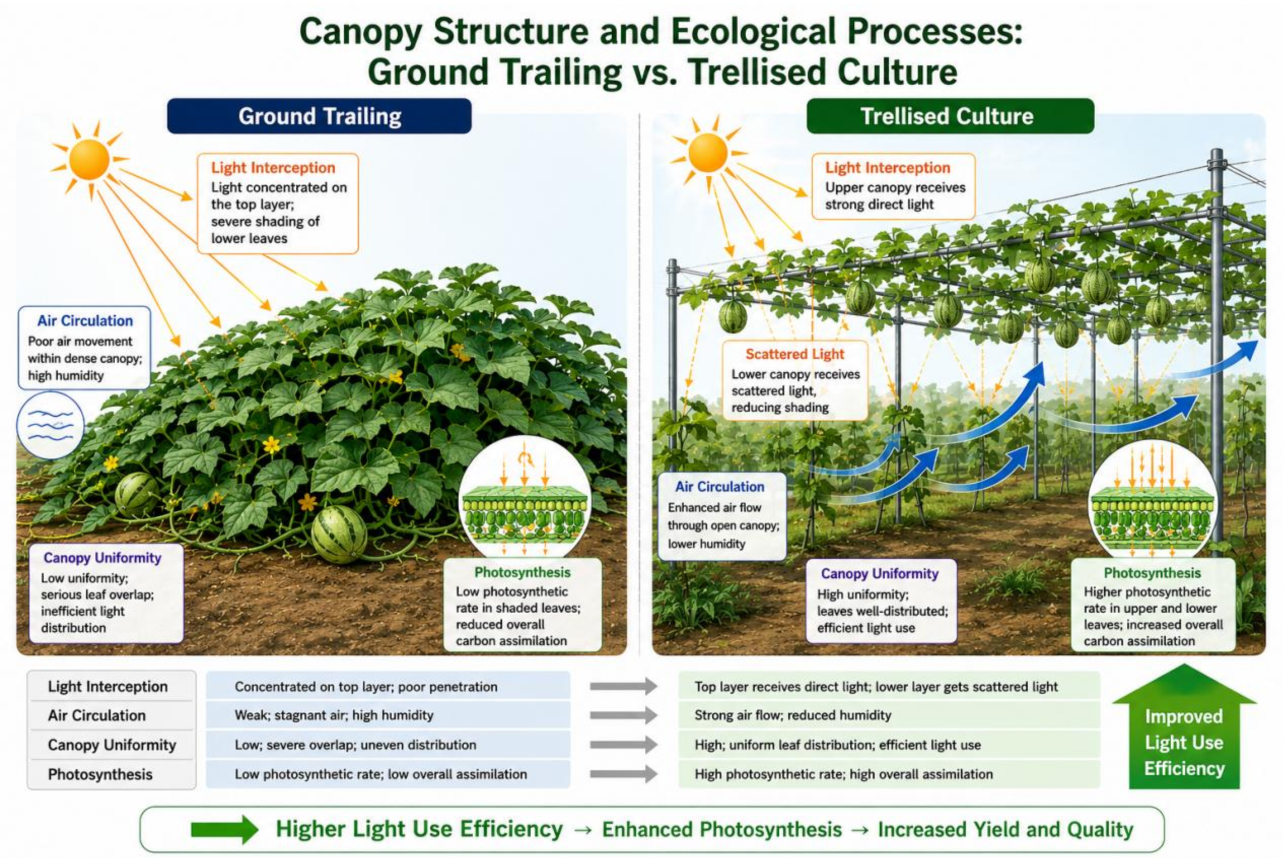

Figure 1 Conceptual illustration of how trellising systems modify canopy architecture, light interception, and air circulation in sponge gourd cultivation

For sponge gourd and related cucurbits, these ecological effects translate into concrete agronomic benefits. In Sri Lanka, supporting vines on horizontal trellises increased fruit yield and quality compared with prostrate growth, providing a basis for developing a full agronomic package for the crop. Comparisons of training systems show that above-ground structures such as bower or high trellis consistently produce higher yields, greater fruit size, and longer vines than ground trailing, underscoring the importance of lifting the canopy to exploit vertical space and reduce shading within the foliage layer (Thakur and Pathania, 2025). Beyond yield, trellising simplifies management operations, enables better disease surveillance, and facilitates integration with practices such as mulching, nutrient management, and direct sowing layouts that orient trellis mesh to optimize natural light exposure and space use in diverse soils and climates.

3 Major Trellising Systems and Their Technical Characteristics

3.1 Horizontal pergola trellis system

Horizontal pergola or bower systems create an overhead canopy that maximizes interception of solar radiation and leaf area, which can substantially increase yield and fruit quality in climbing crops. In sponge gourd, above-ground bower training produced the highest yield, fruit number, and vine length compared with netting and ground trailing, indicating that an overhead horizontal framework effectively exploits the vigorous vine habit (Thakur and Pathania, 2025). Similar pergola systems in grape and kiwifruit have been associated with higher productivity and improved quality composition, supporting the general principle that spreading canopies on horizontal roofs enhances assimilation and crop performance when light is abundant (Danko et al., 2024).

However, traditional pergolas can be labor-intensive and difficult to manage due to their height and dense canopy, which complicates pruning, harvesting and plant protection. In grapevine, horizontal pergola trellises are reported to increase yields 2-3 times relative to vertical systems but require more time-consuming manual operations with arms raised above the head, highlighting ergonomic and cost constraints. New “mobile pergola” or modified overhead designs attempt to retain the yield gains of horizontal canopies while permitting temporary vertical positioning during pruning and harvesting, illustrating a broader trend toward pergola-inspired but more manageable systems that could be relevant for intensive Luffa cultivation.

3.2 A-frame and fence trellis systems

T-type and A-frame trellises represent intermediate architectures between horizontal pergolas and strictly vertical systems, often using sloped or cross-arm structures to support hanging vines. In ridge gourd, a T-trellis achieved the highest marketable yield (24.8 t ha^{-1}) among six systems, outperforming ground trailing and simple staking while providing a better benefit-cost ratio than the locally common pandal system, which produced similar yields but higher costs (Sen et al., 2023). These results suggest that for Luffa crops, moderately elevated, cross-armed trellises can balance canopy expansion, fruit exposure, and construction costs, making them attractive for organic and smallholder systems.

For other cucurbits, A-frame, V, and inverted-V trellises have been tested alongside bower, netting, and cage systems, with bower often giving the highest yield per hectare but inverted-V trellises showing superior benefit-cost ratios, indicating economic advantages despite slightly lower yields (Singh et al., 2023). Farmers may also use simple fence-like supports; while detailed quantitative data for fence systems in Luffa are limited, experiences from ridge gourd and bottle gourd imply that structured supports consistently outperform ground trailing in fruits per plant, total yield, and net returns, pointing to broad benefits of moving vines off the soil surface.

3.3 Vertical training and innovative three-dimensional trellis systems

Strictly vertical or high-wire trellising arranges shoots upward along single or double planes, improving plant density, pollination efficiency, and management access. In sponge gourd, cultivation on a 3-m high trellis increased yield by 33.41% over control and produced yields comparable to bower systems, leading to recommendations for both bower and high trellis training in commercial practice. Vertical training in cucumber and bottle gourd similarly enhanced fruit number per plant, total yield and uniformity, especially when combined with optimized plant growth regulators or bower-type support, underscoring the value of precise canopy orientation in cucurbits (Manna and Singh, 2024).

Emerging three-dimensional and multi-layered systems extend vertical concepts by creating stacked or umbrella-shaped canopies that manage light gradients and microclimate more precisely. In kiwifruit, an umbrella-shaped trellis derived from overhead pergolas more than doubled yield relative to a traditional pergola while maintaining external fruit quality and improving internal quality through better shading of the fruiting canopy (Deng et al., 2023). Outside orchards, innovative tower-based vertical cultivation devices partition three-dimensional space into chambers with differentiated light, temperature and humidity, achieving large water savings and more efficient use of vertical volume, which conceptually parallels multi-tier trellising for high-density vine crops. Together, these developments indicate that future Luffa trellis designs may evolve toward configurable, three-dimensional systems that fine-tune light interception, labor efficiency, and fruit quality beyond what simple horizontal or single-plane vertical trellises can provide.

4 Effects of Trellising Systems on Sponge Gourd Growth and Development

4.1 Effects on plant morphological characteristics

Trellising and training systems markedly shape vine architecture, vegetative growth, and canopy structure in climbing crops, with clear implications for Luffa and related cucurbits. In organically grown ridge gourd, six trellis types produced distinct vine growth responses: the farmer-standard pandal trellis favored somewhat more vigorous vegetative growth, whereas a T-trellis gave slightly higher yields and better fruit quality despite similar growth metrics, indicating that subtle architectural changes can redirect assimilates without necessarily increasing total vine size. In greenhouse cucumber, a single-head training system produced the longest vines and largest leaf area at multiple growth stages compared with umbrella and low-middle systems, showing that more vertical, simplified training can promote extension growth and canopy expansion under protected conditions (Shivaraj et al., 2020).

Similar structural effects are evident in perennial trellised fruit crops. In dragon fruit, a single-pole training system promoted “balanced growth,” whereas a T-trellis enhanced vegetative expansion with wider plant spread but also induced stress symptoms such as canopy overheating and photodamage, illustrating that vigorous morphological growth can be decoupled from functional canopy health (Karunakaran et al., 2026). In grape, fan-shaped and divided-canopy trellis systems increase shoot vigour, shoot leaf area and total leaf area per vine relative to vertical single-curtain systems, confirming that three-dimensional trellis designs can generate larger, more voluminous canopies that must then be managed to balance vegetative and reproductive sinks.

4.2 Effects on leaf photosynthetic performance

Trellis-induced canopy architecture strongly conditions the light environment and thus leaf-level photosynthesis. In high-density mango, a Y-trellis form improved photosynthetic photon flux density in both upper and lower canopy layers compared with open-centre and espalier canopies, and this arrangement supported higher net photosynthetic rates and stomatal conductance at both heights, indicating that moderate light interception with better vertical distribution enhances whole-canopy gas exchange (Kishore et al., 2023). In dwarf mango trained as open-vase versus espalier-trellis, digital canopy modelling showed that the espalier system increased light distribution efficiency per unit leaf area and, when normalized by leaf area, achieved a small productivity advantage, underscoring that trellis geometry can improve photosynthetic efficiency even when total leaf area is reduced (Cheesman et al., 2025) (Figure 2).

Comparative studies in pear and peach further link trellis systems with photosynthetic performance. Pear trees trained on a flat-type trellis exhibited higher net photosynthetic rates than a freestanding system, especially in interior canopy leaves on the sunny side, and transcriptomic analyses implicated enhanced light-harvesting and circadian-clock regulation under the open trellis architecture. In peach, a planar 2D “fruiting wall” training system had lower overall light interception than a 3D Quad-V canopy but achieved 15%-20% higher net photosynthetic rates and better water-use efficiency, particularly maintaining higher photosynthetic efficiency in the shaded lower canopy, illustrating that trellis-driven light uniformity can outweigh total intercepted radiation for photosynthetic performance (Chatzieffraimidis et al., 2025).

4.3 Effects on flowering, fruit set, and assimilate allocation

Training and trellising interact with flowering and fruiting through their influence on canopy microclimate, source–sink relations, and competition among reproductive structures. In dragon fruit, a single-pole system advanced floral initiation (26 days to flowering) and supported higher yields than T-trellis or pyramid forms, suggesting that more favorable light distribution and reduced stress within the canopy can accelerate flowering and enhance fruit set (Karunakaran et al., 2026). Under the same species, experiments in trellised pitaya showed that leaving more cladodes per meter increased flowering intensity, but fruit set and fruit size were largely independent of pruning level; instead, fruit weight declined when more than one fruit developed per cladode, and flower bud drop increased on cladodes bearing many flowers, indicating strong intra-shoot competition for assimilates between flowers and developing fruits (Chiamolera et al., 2023).

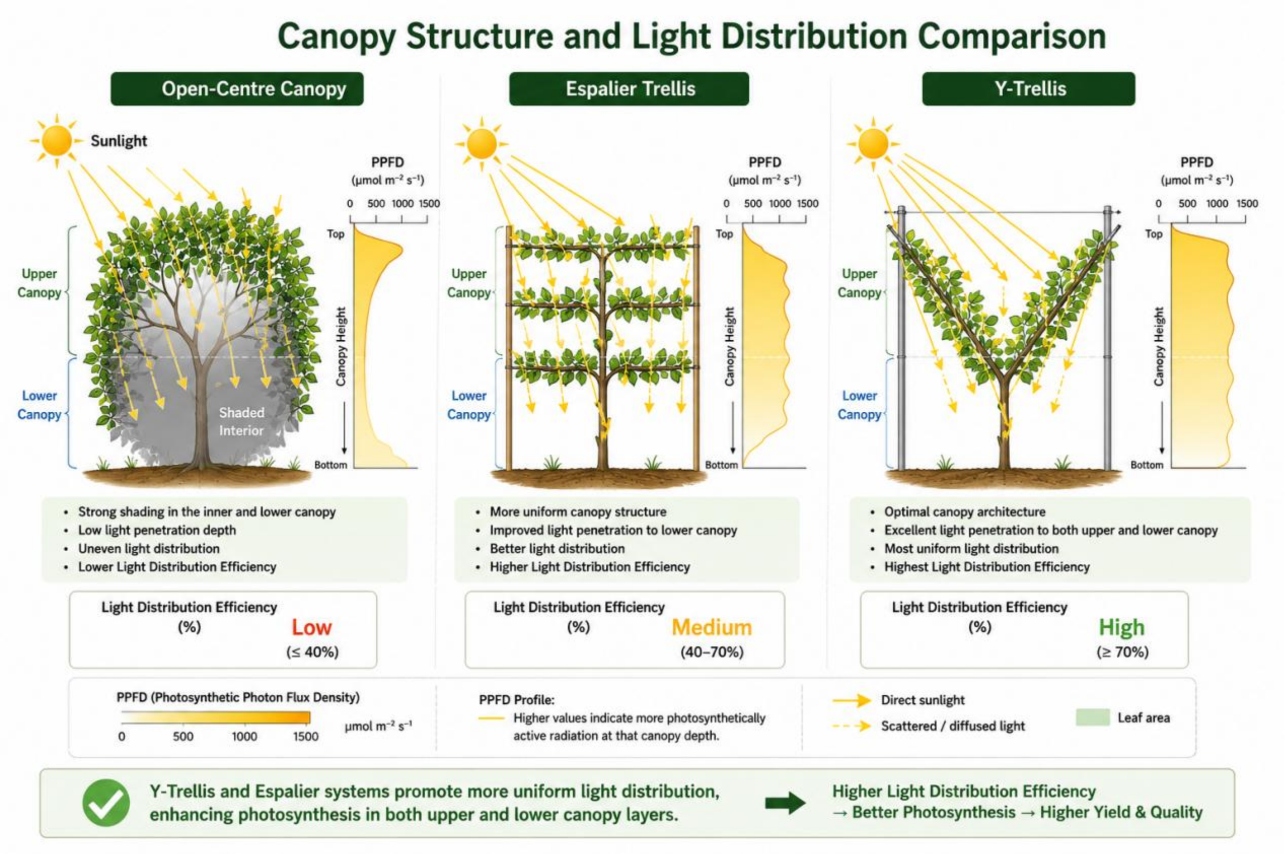

Figure 2 Conceptual comparison of canopy light distribution under open-centre, espalier, and Y-trellis training systems

Cucurbit studies illuminate how resource status and canopy structure affect sex expression and assimilate allocation. In monoecious cucumber, increased nutrient supply raised the number of female flowers and altered the male:female ratio, while pollination level changed female flower numbers during later flowering and affected fruit growth and seed set, yet the total number of fruits and overall seed output per plant did not increase proportionally, implying that reproductive allocation is buffered and not always optimally matched to initial flower production (Gao et al., 2021). Simulation work in cucumber canopies shows that when total biomass production is low, a greater fraction of assimilates is partitioned to leaves and stems to increase light interception, reducing allocation to fruits and increasing investment in side shoots; this demonstrates a structural-functional feedback whereby canopy architecture and light capture demands can divert assimilates away from reproductive sinks.

5 Effects of Trellising Systems on Yield Formation

5.1 Effects on fruit number and individual fruit weight

Trellising systems markedly influence fruit number per plant in Luffa and related cucurbits. In sponge gourd, above-ground training on bower and netting systems significantly increased fruits per plant compared with ground trailing, with the bower system giving the highest fruit number and total yield (Thakur and Pathania, 2025). Similar patterns appear in bottle gourd, where bower training produced the highest number of fruits per vine and yield per hectare, outperforming ground trailing and other training systems.

Effects on individual fruit weight are more nuanced. In sponge gourd, single-plant vertical training produced the highest average fruit weight, whereas the bower system maximized fruit number and overall yield, indicating a trade-off between fruit size and fruit load under different trellises. In bottle gourd, trailing systems increased fruit number and total fruit weight per plant, but training systems altered fruit diameter and other size traits, suggesting that trellis design can shift assimilate allocation between fruit number and individual fruit mass (Singh et al., 2023).

5.2 Regulatory mechanisms of trellising systems on yield components

Differences in fruit number and weight among trellis systems are closely linked to canopy light distribution and the balance between vegetative and reproductive sinks. In hydroponic cucumber, a modified-umbrella trellis increased fruit number and fruit weight per plant relative to a high-wire system, largely because directing apical meristems downward improved light access to the most photosynthetically active leaves within the canopy. Modeling work shows that increased solar radiation interception raises individual cucumber fruit weight, while excessive shading in umbrella-type systems reduces lower-canopy contribution and can trigger fruit abortion, illustrating how trellis-driven LAI and light gradients regulate yield components (Kile et al., 2024).

At the physiological level, trellises also alter hormonal balances and assimilate partitioning. In kiwifruit, an umbrella-shaped trellis more than doubled yield compared with a traditional overhead pergola, partly by promoting vegetative growth of canes in the most productive diameter class and creating an upper shading canopy that improved pigment accumulation and hormonal status in the fruiting zone .The most productive cane zones under this system contained higher levels of cytokinin and auxin and favorable ratios with gibberellin and abscisic acid, suggesting that trellis-induced changes in canopy structure can indirectly regulate flower bud differentiation and fruit set through hormone dynamics (Deng et al., 2023).

5.3 Yield enhancement under different ecological conditions

Trellis systems interact strongly with ecological conditions such as season, radiation level and planting density to shape yield responses. In sponge gourd, above-ground training on bower or netting markedly increased yield over ground trailing under open-field conditions, with yield gains up to 71% in some systems, showing that elevating the canopy improves performance in typical subtropical environments (Thakur and Pathania, 2025). Off-season trellis cultivation of bottle gourd further indicates that while absolute yield per area can be lower in hotter or less favorable seasons, trellis-based systems may still provide higher net returns due to advantageous market prices, highlighting economic resilience across seasons.

In greenhouse cucumbers, interactions between canopy structure, light environment and trellis type are especially pronounced under low irradiance. Inter-lighting within a high-wire canopy improved photosynthetic characteristics of lower leaves but did not increase total fruit production because extreme leaf curling reduced horizontal and vertical light interception, demonstrating that architectural responses can negate potential gains from improved light distribution. Modeling of intracanopy lighting similarly predicted that, in the absence of such morphological issues and with unchanged partitioning, fruit yield could increase by about 8%, largely through enhanced light absorption, emphasizing that under constrained light climates, trellis-lighting combinations must maintain favorable canopy architecture to fully realize yield enhancement (Trouwborst et al., 2011).

6 Effects of Trellising Systems on Fruit Quality

6.1 Effects on external fruit quality attributes

Trellis systems often improve external appearance traits such as color uniformity, size, and shape, which are critical for Luffa market acceptance. In acorn squash, trellised plants produced fruits that were more uniformly black-green and firmer than those from ground culture, indicating reduced blemishes and more consistent epidermal development under supported growth (Adeeko et al., 2024). Trellising also increased fruit length in greenhouse cucumber, where a high-wire system produced the longest fruits, suggesting that vertically oriented canopies can favor more elongated, regular fruit shape (Figure 3).

Figure 3 Representative comparison of fruit appearance under ground-trailing and trellised cultivation systems

External size and mass may likewise benefit from combined trellis and floor management. In spaghetti squash, using both trellis and mulch gave the greatest number of fruits per plant and the largest fruit weight, while also supporting longer and wider fruits compared with other combinations, indicating synergistic effects of vertical support and soil surface protection on fruit growth (Kartika and Karyana, 2017). For bottle gourd, bower training significantly increased fruit length relative to ground trailing, even though fruit diameter could be slightly reduced, implying that supported systems may shift proportions toward more cylindrical, market-preferred shapes (Singh et al., 2023).

6.2 Effects on nutritional quality characteristics

Evidence from cucurbits and other trellised crops indicates that canopy architecture can alter internal composition, including sugars, acids, and secondary metabolites. In trellised acorn squash, fruits showed very high dry matter and soluble solids at harvest, and trellised plants had higher carotenoid, ascorbate, and antioxidant contents than ground-grown plants, reflecting enhanced accumulation of both energy reserves and health-promoting compounds (Adeeko et al., 2024). Similarly, in table grapes, a T-trellis system increased total anthocyanin, flavonoid, proanthocyanidin and monoterpene contents compared with a V-trellis, demonstrating that trellis geometry can modulate phenolic and aroma profiles important for nutritional and sensory quality (Wang et al., 2023).

Trellis-related changes in microclimate and sink–source balance can also influence basic quality indices such as soluble solids and titratable acidity. In greenhouse cucumber, training systems affected total soluble solids and potassium content: fruits from V-shape systems had the highest soluble solids and K, suggesting that certain vertical arrangements promote greater sugar and mineral accumulationFor sweet acorn squash grown on trellises, dry matter and soluble solids remained high even after extended cold storage, with TSS values around 19-20 °Brix, indicating that trellis-grown fruits can maintain dense, sweet flesh and nutritional richness over time.

6.3 Effects on marketability and postharvest quality

Trellis systems frequently enhance overall marketability by increasing the proportion of marketable fruit and extending shelf life. For spaghetti squash, the use of trellis and mulch together produced more marketable fruits and heavier fruit weight, which directly improves pack-out and economic return per plant. In cucumber, trellising doubled marketable yield compared with ground culture and reduced the proportion of fruits with defects such as yellow belly, jumbo size, and distortion, indicating fewer downgraded culls and a higher share of Fancy-grade produce.

Shelf life and storability can also benefit from trellis-based systems through effects on firmness, color retention, and disease incidence. In long English cucumber, training systems that increased canopy light penetration produced darker green fruits with longer shelf life, linking trellis-induced light exposure to chlorophyll retention and delayed surface yellowing. For trellised, greenhouse-grown sweet acorn squash, appropriate cold storage (10 °C-15 °C with reduced humidity) allowed up to 3 months of shelf life with minimal quality loss, and trellis cultivation produced uniformly colored, high-quality fruits that responded well to postharvest treatments such as hot water brushing to reduce rots, supporting steady, extended marketing (Adeeko et al., 2020).

7 Case Study: Comparative Performance of Different Trellising Systems on Sponge Gourd Yield and Quality

7.1 Comparison of horizontal pergola and a-frame trellis systems

Horizontal pergola and related overhead systems can greatly increase canopy area and light interception but differ from A-frame or T-type structures in labor needs and yield response. In grape, pergola trellises allow maximum "green mass" and solar energy assimilation, raising yields by 2-3 times compared with vertical systems, though management becomes much more labor-intensive due to overhead work (Kharibegashvili et al., 2021). A mobile pergola design mitigates these drawbacks by shifting between horizontal and vertical positions, maintaining pergola-level yield while simplifying pruning and harvesting, which illustrates the trade-off between productivity and ergonomics inherent in fully horizontal systems.

A-frame or T-type trellises usually provide intermediate canopy height and partial horizontal spread. In organically grown ridge gourd (Luffa acutangula), a T-trellis produced the highest marketable yield (24.8 t ha^{-1}) and the best benefit-cost ratio among six trellis types, slightly outperforming the locally used pandal system despite similar vegetative growth (Sen et al., 2023). In passion fruit, a horizontal "T" system achieved intermediate productivity between simple and total trellis structures, reflecting that partially horizontal designs may not always maximize yield but can balance structural cost, fruit quality, and cultural operations (Cleves-Leguízamo, 2021).

7.2 Production efficiency analysis of fence trellis and vertical training systems

Fence-like and simple vertical trellises emphasize linearly arranged canopies, favoring ventilation, pollination and access. In Colombian passion fruit, a simple vertical trellis reached 30.5 t ha^{-1} with 73% first-quality fruit, outperforming a horizontal T-trellis and a full "barbecue" system in both productivity and quality while also enabling higher planting density and mechanization. Similarly, long-term records from Colombian orchards indicate that simple trellises combine good phytosanitary management, efficient foliar spraying, and ease of structural repair, leading to stable high-quality yields over 18-24 month cycles (Cleves-Leguízamo, 2021).

High-wire and other vertical training systems in greenhouse cucumbers highlight additional efficiency dimensions. A high-wire system produced more consistent weekly yields than a modified-umbrella system, even though the latter doubled fruit number per plant and increased total yield, suggesting that vertically oriented canopies can stabilize harvest rhythm at the expense of some productivity. In another high-wire study, training cucumbers on a single main stem per slab achieved the same yield per area as multi-stem configurations while improving water use, simplifying work, and stabilizing weekly production, underscoring that simple vertical architectures can enhance input efficiency and labor organization without sacrificing output.

7.3 Comprehensive evaluation of representative regional cultivation cases

Regional Luffa and cucurbit case studies show that trellis choice interacts strongly with local climate, infrastructure and market conditions. In Sri Lanka, sponge gourd grown under horizontal trellising achieved average yields of 8.4 t ha^{-1} with improved fruit number compared with prostrate vines, indicating clear agronomic benefits of overhead support under tropical field conditions. In subtropical Mexico, direct-sown sponge gourd on live-stake trellis systems produced 5-20 fruits per plant and fruit weights up to 660 g at the best site, with production costs per fruit about one-third lower than at less favorable sites, demonstrating that simple wire-and-stake frameworks can support profitable small-scale production in diversified landscapes (Fernández-Lambert et al., 2025).

Beyond Luffa, other cucurbits underline how trellising adapts to regional constraints. In North Florida, A-frame and wire-trellis cucumbers showed no significant yield advantage over conventional ground culture, suggesting that in humid subtropical climates with certain cultivars and management, trellising may primarily improve handling and fruit cleanliness rather than yield. In Israel, winter-grown acorn squash under protected cultivation yielded 56% more when trellised, with fruits that were firmer, better colored and richer in dry matter, soluble solids, carotenoids and antioxidants, illustrating that in high-value, protected systems, vertical trellising can simultaneously raise productivity and quality to meet premium markets (Adeeko et al., 2024).

8 Trellising Systems, Production Efficiency, and Sustainable Development

8.1 Effects on labor requirements and production costs

Trellis design strongly influences both variable and fixed production costs in cucurbit systems. In organically grown ridge gourd, the T-trellis produced the highest marketable yield while using simpler materials than the locally common pandal, resulting in the highest benefit-to-cost (B:C) ratio across varieties and demonstrating that trellis choice can improve profitability even when yield differences are modest. Off-season trellis-based bottle gourd cultivation likewise showed only small differences in cultivation cost between seasons, yet off-season crops achieved substantially higher net returns and B:C ratio due to better prices, underlining how trellis systems can support profitable timing strategies (Singh et al., 2024).

Labor requirements are also shaped by trellis structure and associated training operations. In highbush blueberry, adding a V-trellis increased pruning time in some years without compensating yield gains, raising total pruning and harvest costs per kilogram relative to a standard T-trellis and highlighting the risk that more complex trellises can raise labor costs (Strik and Davis, 2022). Conversely, improved training concepts in cucumber, such as lowering-type systems, have simplified repetitive tasks like old leaf removal and harvesting, pointing to the potential for trellis designs that facilitate partial or full automation of key operations.

8.2 Effects on disease and pest management as well as field operations

Raising cucurbit canopies on trellises can indirectly aid disease and pest management through improved aeration and reduced soil contact. In sponge gourd, horizontal trellising increased yield and fruit quality compared with prostrate vines, and pest and disease observations showed only mild leaf miner and low fruit fly damage, supporting the view that Luffa can be grown with minimal external inputs and low production costs when properly supported (Silva et al., 2012). Field studies with trellised cucumbers in open ground report that air exchange between plants improves, soil moisture is better managed, fruit quality improves, and soil-borne diseases decrease, illustrating multiple sanitary and operational benefits of the trellis method over conventional culture.

Interactions between trellising and targeted pest-management tools are also important. In slicing cucumber, trellising reduced downy mildew necrosis slightly and increased total fruit yield by about 15%, but trellising alone did not raise marketable yield; fungicide applications remained the main driver of disease suppression and marketable production, indicating that support structures must be integrated with chemical or biological controls (Keinath, 2019). More generally, trellis-based vegetable systems are recognized as a component of sustainable production that can lower overall production costs, improve food quality, and support organic methods by enhancing sunlight interception, aeration, and reducing pest and disease contact, thereby easing field operations like harvesting and crop inspections (Singh et al., 2024).

8.3 Prospects for trellising cultivation in sustainable and high-efficiency production

Trellis systems are increasingly framed as a cornerstone of sustainable intensification, enabling higher yields per unit ground area and more efficient use of vertical space. A recent agrivoltaic design study noted that using trellises can double or triple yield per acre while reducing diseases and pests, easing harvest, and producing cleaner crop products, and proposed low-cost wood-based PV racking that simultaneously functions as trellis support and irrigation/fertigation infrastructure. For small and marginal farmers, multilayer trellis farming and off-season trellis-based production have repeatedly outperformed traditional systems in net returns and profit, suggesting a pathway to livelihood improvement and more resilient production systems (Singh et al., 2024).

Within Luffa specifically, sponge gourd has been identified as a high-potential underutilized cucurbit whose yield and fruit quality are strongly enhanced by trellising, and which can be grown with low external inputs and minimal pesticide use, aligning well with organic and low-input strategies. Broader reviews of dioecious cucurbits emphasize that integrating trellising with mulching, biofertilizers and growth regulators holds "immense potential" for future vegetable production and markets, particularly for minor cucurbits cultivated by smallholders, indicating that optimized trellis systems can be central to high-efficiency, resource-conserving production chains (Nayak et al., 2024).

9 Future Perspectives and Conclusions

Existing studies on Luffa and related cucurbits show that trellising can clearly increase yield and improve fruit quality, but the evidence base is still narrow and fragmented. Most work focuses on short-term comparisons of a few trellis designs at single sites and seasons, often without detailed characterization of plant physiology, microclimate, or fruit quality beyond basic traits. For sponge gourd, for example, horizontal systems were identified as promising, yet evaluations were confined to limited environments and short time frames, with explicit calls to repeat experiments across more seasons and to expand trait coverage. Another major limitation is that trellis research on Luffa is largely decoupled from other technological advances in crop management. Studies rarely integrate trellising with rootstock use, controlled environments, or detailed monitoring of water and nutrient dynamics, even though grafting and soilless culture have proved effective for improving yield and quality in closely related cucurbits. Economic and labor aspects are also underexplored: while some work on ridge gourd has compared benefit-cost ratios among trellises, there is little quantitative analysis of labor ergonomics, long-term structural costs, or adoption barriers among smallholders who still rely on fences or trees for support.

Rapid progress in precision agriculture and IoT provides a rich toolbox that has scarcely been applied to Luffa trellis systems. Cloud-based platforms and wireless sensor networks have already been used to monitor greenhouse microclimate, automate control, and increase cucumber yield and quality in soilless systems, demonstrating the potential of data-driven management. Similar sensor architectures, combined with simple actuators, could be adapted to trellised Luffa to control irrigation, fertigation, and possibly shading or ventilation based on real-time canopy and weather data. Beyond basic monitoring, next-generation "smart trellises" could embed low-cost sensors and edge computing into the support structure itself. Reviews of smart sensors and IoT in agriculture emphasize the value of continuous measurements of plant stress, soil moisture, and microclimate, coupled with artificial intelligence for predictive decision-making. Integrating these capabilities with modular, adjustable trellis designs would allow dynamic management of canopy density, pruning, and harvest timing in response to incoming light, temperature, and plant status, linking structural design with automation and making intensive Luffa systems more resilient and resource-efficient.

Overall, research to date indicates that lifting Luffa vines from the ground onto engineered trellises reliably increases total yield, mainly by raising fruit number without compromising basic external quality. However, the optimal trellis configuration clearly depends on cultivar, environment, and production goals, and current evidence is insufficient to define robust design principles across regions. Experience from ridge gourd and other cucurbits suggests that relatively simple, moderately elevated systems can offer a favorable balance of yield, fruit quality, and cost, but systematic comparisons with horizontal pergolas, vertical walls, and three-dimensional designs remain scarce. Future studies on Luffa trellising should therefore be multi-season and multi-site, combining detailed measurements of growth, canopy light distribution, and fruit nutritional quality with rigorous economic and labor analyses. There is particular need to test trellis systems under stress conditions such as heat, salinity, and water deficit, where grafting onto tolerant Luffa rootstocks, IoT-based greenhouse or field control, and soilless cultivation are already showing promise in other cucurbits. Integrating these technologies into comprehensive, sensor-informed trellis packages, and co-designing them with farmers for different ecological and market contexts, will be essential to fully exploit the yield and quality potential of Luffa as an emerging high-value crop.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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